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Utah State University Contract 93-1070, amendments 3 and 6
(Flaming Gorge Studies: Reproduction and recruitment of Gila spp. and Colorado squawfish in the middle Green River)

A GEOMORPHIC ASSESSMENT OF THE AVAILABILITY OF POTENTIAL HUMPBACK CHUB HABITAT IN THE GREEN RIVER IN DESOLATION AND GRAY CANYONS, UTAH

DRAFT FINAL REPORT

K. Lynn Orchard

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John C. Schmidt

Department of Geography and Earth Resources

Utah State University

Logan, Utah 84322-5240

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ABSTRACT

The size and number of low-velocity eddies that may be preferred habitat for the endangered humpback chub (*Gila cypha*) in the Green River in Desolation and Gray Canyons changes with discharge and has changed since the early 1900's. We determined the present extent and distribution of these habitats by mapping low-velocity eddies at a scale of 1:5000 at 5 or 6 discharges between 2,100 and 27,000 ft^3/s in four 8-km reaches that are regularly sampled by the Utah Division of Wildlife Resources. We also mapped the surficial geology of these study reaches and the distribution of bed substrate that are emergent at 2000 ft^3/s. We analyzed the distribution of these areas within a geographic information system. The availability of habitat prior to completion of Flaming Gorge Dam was estimated by matching old oblique photographs, analyzing old aerial photos, and recomputing habitat availability prior to channel change.

The total area of low-velocity eddies, when summed for the 4 study reaches, does not change with discharge, but the relative distribution of these eddies among the 4 study reaches does change. Also, the type of eddies changes with discharge. At low discharge, the greatest proportion of the total area of low-velocity eddies occurs as small shoreline eddies, but the greatest proportion occurs in a few large eddies at higher discharges. At low discharge, the river bank is highly contorted and is dominantly bare sand and gravel. At high discharge, the river bank has a simpler shape, and much of the shoreline is inundated vegetation.

The Green River channel is 19% narrower today than it was in the 1920's, and riparian vegetation has established itself at low elevations and on formerly active mid-channel islands. We estimate that the substrate of most nearshore habitats was sand or gravel prior to channel narrowing.

For purposes of developing flow recommendations, our results must be integrated with the results of ecological studies which identify the relative importance of the different habitats in the life history of the target species.

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INTRODUCTION

The endangered humpback chub (*Gila cypha*) only lives in those canyon reaches of the Colorado River system where there are abundant debris fans and rapids, such as Desolation and Gray Canyons of the Green River in eastern Utah. In addition to humpback chub, Desolation and Gray Canyons support populations of the endangered Colorado squawfish (*Ptychocheilus lucius*), and contain one of the few known spawning sites of this species. Because the operation of Flaming Gorge Dam has the potential to affect the habitats of these endangered fish, we investigated the relationship between discharge, habitat availability, and habitat distribution in Desolation and Gray Canyons.

Habitat characteristics are determined by flow and substrate conditions. Gravel bars are abundant in these canyons, and much of the banks are composed of coarse debris flow material or talus. However, other banks are composed of sand, silt, and clay deposited as suspended load. Recirculating eddies comprise a large part of the flow field of the river, and there are many regions of upstream or stagnant flow in these canyons. Preferred habitat at different life stages of the humpback chub occur as various combinations of channel substrate, bank material, and local hydraulics. The most comprehensive studies of habitat for these fish at various life stages have been conducted on the Colorado River and the Little Colorado River in Grand Canyon, where the Colorado River's sediment load, temperature, and discharge differ substantially from the relatively unregulated conditions of the Green River. Valdez and Ryel (1995) showed that adult humpback chub spend most of their lives in low-velocity parts of large, recirculating eddies. Converse (1996) found that juvenile humpback chub in Grand Canyon prefer small eddies and low-velocity zones along vegetated shorelines and along some bedrock banks that have overhanging cliffs. In Desolation and Gray Canyons, preliminary findings by Day and Crosby (1997) show that humpback chub, on average, use eddy habitats that were longer, and wider than unused eddies. However, habitat preferences are still not well understood in these canyons. Thus, we identified various combinations of flow and

substrate that have the potential to constitute important habitat. Our purpose was to determine if the size and abundance of these habitats changes with discharge.

Local flow patterns and type of substrate are influenced by seasonal and dam-related changes in discharge. Schmidt (1990) showed that recirculating eddies increase in length with increasing discharge. As discharge increases, shorelines, vegetation, and mid-channel bars are inundated, and the amount of shoreline within eddies changes. Thus, the distribution of desirable habitat may change. Releases from Flaming Gorge Dam influence base-flow of the Green River in Desolation/Gray Canyons as well as the timing and magnitude of spring floods.

Significant changes in the geomorphology of the Green River have taken place during the past century which have the potential to alter the relationship between discharge and habitat. Increases in riparian vegetation, channel narrowing, abandonment of secondary channels, and the subsequent loss of habitat have been well documented in reaches upstream and downstream from Desolation and Gray Canyons (Graf 1978, Allred 1997, Grams 1997). Allred (1997) showed that channel narrowing and simplification near Green River, Utah, occurred during 2 periods. The first period was during the regional drought of the 1930s, and the second period followed the completion of Flaming Gorge Dam. Although the introduction of the non-native tamarisk (*Tamarix* sp.) helped cause narrowing, the primary mechanism was reduced flood magnitudes due to climate change and flow regulation. Because no studies have measured the extent of channel narrowing in Desolation and Gray Canyons, a second objective of this study was to determine if channel narrowing had occurred, and if it had caused a significant effect on discharge/habitat relationships. The purpose of this report is to (1) report measurements of available habitat in 4 representative reaches of Desolation and Gray Canyons at a wide range of discharges, (2) identify and describe geomorphic changes in these canyons, and (3) evaluate how historical changes in geomorphology have altered habitat/discharge relationships over time. For purposes of development of flow recommendations, our results must be integrated

with the results of ecological studies which identify the relative importance of the different habitats in the life history of the target species.

STUDY AREA

Desolation and Gray Canyons are located in eastern Utah where the south-flowing Green River has eroded its course into the Tavaputs Plateau. Although 2 names are attached to the 151-km reach between Sand Wash and Swasey's Rapid (Fig. 1), the reach is more appropriately divided into 3 primary geomorphic divisions; an upstream reach with very low channel gradient and wide channel width, a middle section with steep gradients and abundant debris fans, and a lower section with moderate gradient and very narrow valley and channel widths (Fig. 2; Table 1). Between Sand Wash (RK 347.6) and Jack Creek (RK 305.8), channel gradient is very flat and the channel plan form is a series of fixed meanders where alluvial terraces occur on alternating banks of the river. This section of the river is the continuation of the southern Uinta Basin and fixed meanders extend upstream to Ouray. The second geomorphic reach is located approximately between Jack Creek and the Roan Cliffs (approx. RK 253). The dip of the sedimentary rocks of the region is to the north, and the Tavaputs Plateau increases in elevation to the south. As a result, the depth of Desolation Canyon increases downstream. Downstream from Jack Creek, channel gradient steepens. Bedrock becomes more resistant, and debris flows become more frequent and deliver coarse sediment to the channel. The Roan Cliffs mark the southern limit of Desolation Canyon. The third major geomorphic division occurs downstream from this point, where the river establishes its course in the Mesa Verde formation. This reach's southern limit is the Book Cliffs near Swasey's Rapid (RK 212.4) and the town of Green River.

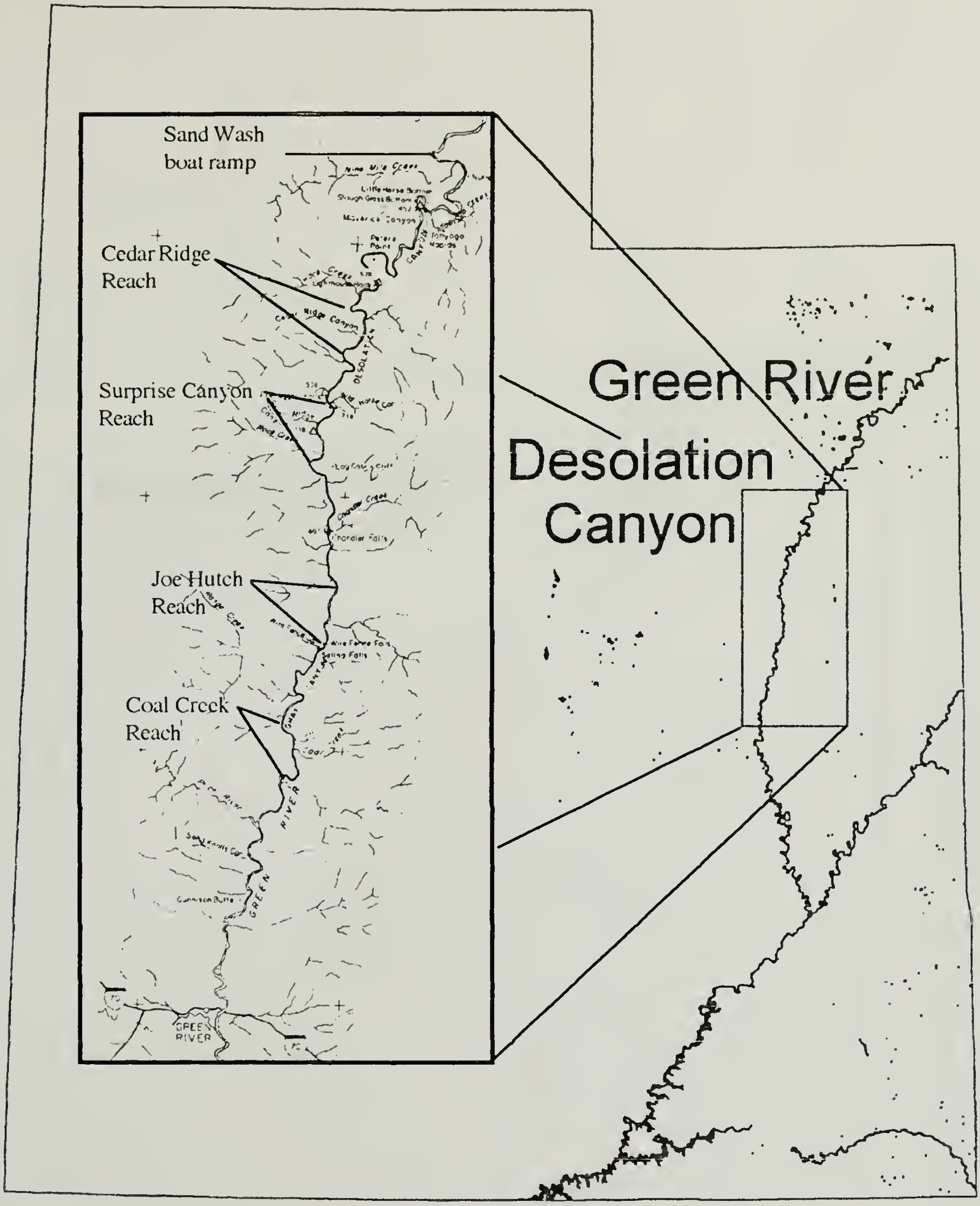


Figure 1. Study reaches located in Desolation and Gray Canyons of the Green River in Eastern Utah.

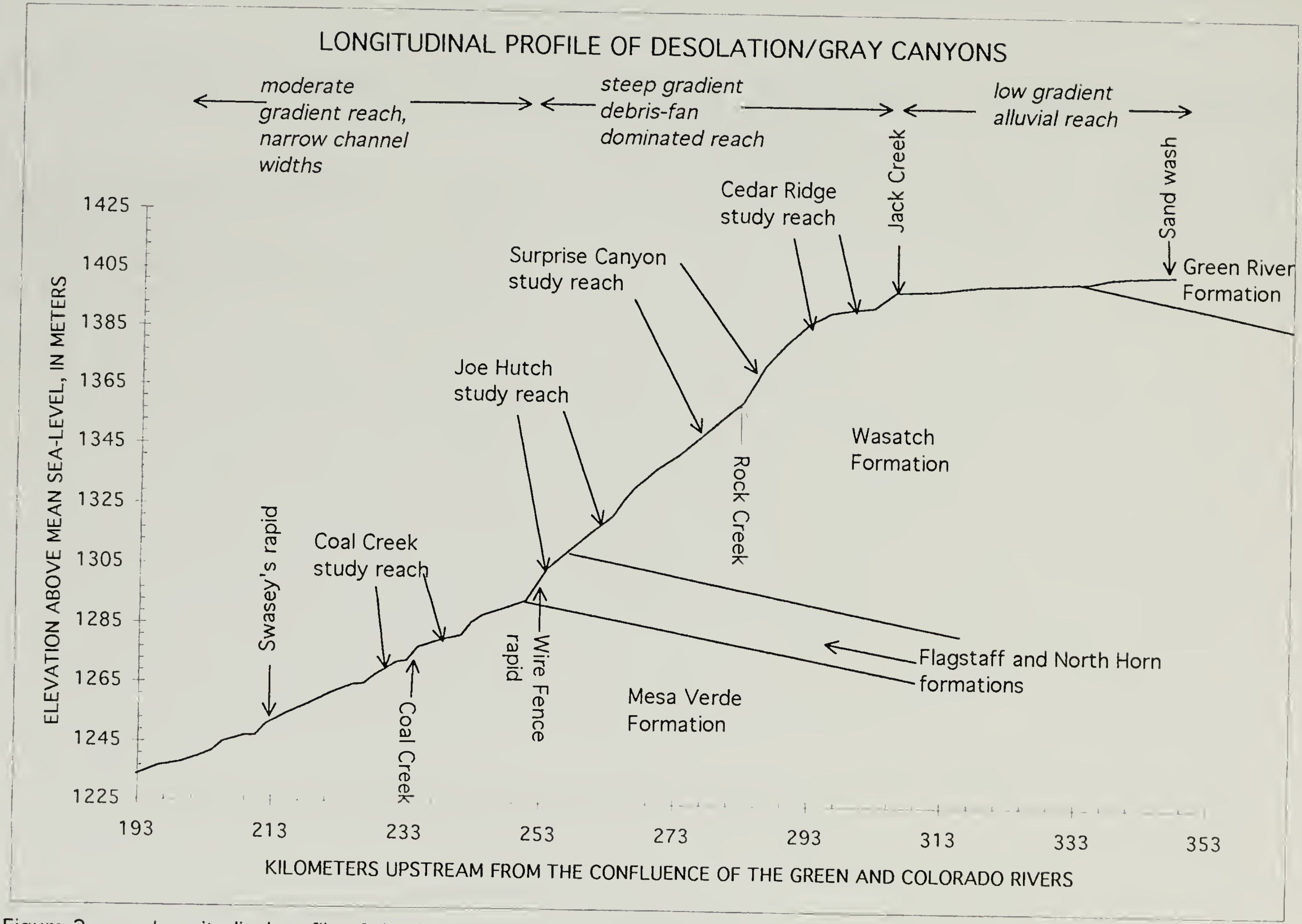


Figure 2. Longitudinal profile of the Green River in Desolation and Gray Canyons showing the 4 study reaches, and their location in relation to the 3 major geomorphic divisions of the canyons. Survey data for profile taken from Merriman (1940)

TABLE 1. SUMMARY OF REACH CHARACTERISTICS WHICH ARE INFLUENCED BY THE PREDOMINANT BEDROCK GEOLOGY

STUDY REACH	BEDROCK AT RIVER LEVEL	GRADIENT m/m	PERCENT OF SHORELINES AT BANKFULL STAGE IN CONTACT WITH BEDROCK, TALUS OR DEBRIS-FAN MATERIAL	AVERAGE WIDTH OF ALLUVIAL VALLEY (m)	AVERAGE CHANNEL WIDTH (m)	PERCENT OF ALLUVIAL VALLEY OCCUPIED BY ACTIVE CHANNEL
CEDAR RIDGE	Green River/Wasatch	0.00057	24	323	120	37
SURPRISE	Wasatch	0.00250	54	271	109	40
JOE HUTCH	Wasatch/Flagstaff/North Horn	0.00183	33	422	129	31
COAL CREEK	Mesa Verde	0.00126	52	138	99	72

The 4 reaches used in this study were established by UDWR biologists (T. Chart, UDWR, per. comm.). The study reaches are located between river kilometers 301.7 and 293.6, 286.9 and 278.4, 262.8 and 253.8, and 238.5 and 230, where locations are measured in kilometers upstream from the confluence of the Green and Colorado Rivers. We refer to these reaches as the Cedar Ridge, Surprise Canyon, Joe Hutch, and Coal Creek study reaches, respectively. Each study area is approximately 8 km in length and has a slightly different geomorphic setting determined largely by the dominant bedrock at river level (Table 1).

In the upstream parts of Desolation Canyon, the river's course is established in the lacustrine Green River formation. Deposited in the Paleocene Lake Uinta, this formation consists of alternating shales, carbonate mudstones and sandstones. This formation is highly susceptible to weathering, and the river has eroded a wide alluvial valley. There are few debris fans, and the channel is shallow and wide. The channel banks are vertically-accreted floodplains, and terraces are comprised of fine sands and silts. These deposits are covered with dense mature tamarisk and box elder (*Acer negundo*) stands which often overhang the river and form impenetrable barriers at river's-edge. Bed material is predominantly sand.

The most upstream study reach is Cedar Ridge, which begins where the river-level bedrock changes to the sandstones of the Wasatch formation, and the valley changes from the low-gradient alluvial section to the high-gradient debris-fan affected-reach. The whitish-green color of the reducing lake bottom environment of the Green River formation gives way to the bright reds of the fluvial Wasatch formation. The Wasatch is predominantly a resistant sandstone deposited by streams than once flowed into the closed basin containing Lake Uinta. Small fluctuations in lake level caused the shallow lakes' shoreline to fluctuate over a wide area. As a result, the Wasatch and Green River formations are highly intertounged and almost indistinguishable from each other through much of the Cedar Ridge reach. Bedrock becomes progressively more resistant

downstream, and the alluvial valley gradually narrows from a wide alluvial reach to a confined canyon, and the channel contains characteristics of both. The alluvial valley is wide and filled with broad low angle debris fans which form small rapids. The river has a low gradient between rapids, and is lined by dense vegetation and fine-grained banks.

The Surprise Canyon reach is approximately 8 km downstream from the Cedar Ridge reach; the Wasatch formation sandstones are the dominant bedrock in this reach. The alluvial valley is narrower, gradient is higher, and abundant debris fans create numerous riffles and small rapids. Vegetation is sporadic ranging from dense stands of tamarisk and willow on alluvial terraces to unvegetated debris fan and talus deposits.

The Joe Hutch study area begins near the downstream end of Desolation Canyon. The canyon walls recede from the river, and the Wasatch formation erodes away in the stair-like escarpment of the Roan Cliffs. As the Wasatch formation erodes back, the alluvial valley widens and the siltstones and shales of the Flagstaff and North Horn formations appear at river level. Several large debris flows have occurred recently in this reach. Rapids are larger than those found upstream and reflect the increased debris flow activity. The two largest rapids in Desolation Canyon , Wire Fence and Three Fords, occur about 1 km downstream from this reach.

The Coal Creek study reach is the farthest downstream and is within Gray Canyon. The river in this reach is narrowly confined by a cliff-forming sandstone member of the Cretaceous Mesa Verde formation. The alluvial valley is almost completely constrained by bedrock cliffs which often rise vertically from the waters' edge. Debris flows entering the channel here do not enter a broad alluvial valley, and fans are often narrow and steep. Large recirculating eddies occur downstream from these fans.

METHODS

Flow patterns and the location of shorelines were mapped in the 4 study reaches in order to measure the areal extent and distribution of eddies and low-velocity zones at a wide range of discharges. These data were combined with data describing substrate and bank

materials. Maps were made at discharges between 2,100 and 27,000 ft^3/s. Surficial geology of the river corridor was mapped to determine the distribution of alluvial deposits, and to compare and contrast the relationship between these deposits and available habitat in each of the study reaches. Cross sections of the channel were measured to help characterize the geomorphic variability within and between reaches. Finally, historical oblique photos taken in Desolation and Gray Canyons were located through archival searches. These photo sites were located in the field, and photos were matched to identify geomorphic changes that have taken place in the past.

Field Mapping-Surficial Geology

Surficial geology of the alluvial valley in the 4 study reaches was mapped in the field in July and September 1996. Maps were drawn onto a transparent mylar overlay of U.S. Bureau of Reclamation 1:5000 scale air photos taken in 1993 at approximately 2000 ft^3/s. The contacts between map units were drawn onto mylar and labeled while viewing the photographs with a stereoscope. Units were distinguished by depositional environment and material. Mapped features were identified on the ground to verify and correct boundary, substrate, and depositional environment delineations.

The extent of the active channel, modern floodplain, and alluvial valley was identified and mapped in each of the 4 study reaches (Fig. 3). The active channel was defined as the approximate extent of the channel which is inundated and reworked with near annual frequency, and was identified in the field from physical evidence of recent inundation. Mapping the active channel occurred at baseflow discharge when the river was low. However, even at baseflow conditions a large area of the active channel is inundated, and much of the bed was not mapped. Specific deposits mapped in the active channel were: talus, debris fans, gravel bars, eddy-deposited sandbars, and mid-channel and channel-margin sandbars. The modern floodplain is a vegetated, low-elevation terrace-like deposit adjacent to the active channel. It is higher in elevation than the active channel, and inundated less frequently. The floodplain is identified on the surficial geologic maps as

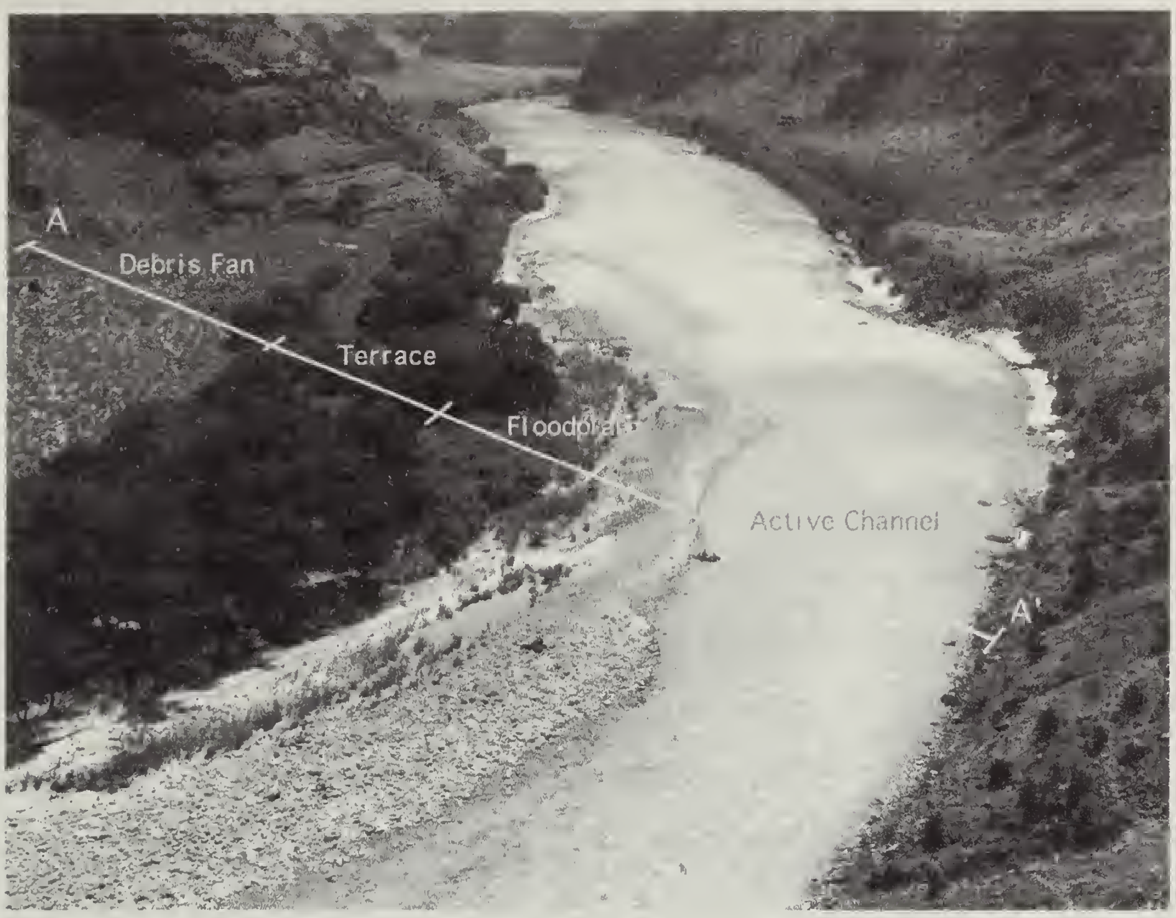


Figure 3. Typical view of the alluvial valley in Desolation Canyon. Line A-A′ spans the entire width of the valley. The active channel is the portion of the alluvial valley regularly inundated, and the floodplain is inundated for a few days in some years. Terraces, and the proximal end of debris fans, are higher in elevation than active channel and floodplain, and are rarely inundated by the river.

vegetated channel-margin fine-grained alluvium. The alluvial valley is the low-elevation valley bottom that contains the active channel and the modern floodplain, as well as other higher elevation alluvial deposits which are not inundated and not part of the active channel or floodplain. These deposits include: terraces, debris fans, and eolian sands. More attention was given to mapping the bank-material in the active channel and floodplain, than higher elevation, inactive deposits, which impact fish habitat indirectly. The distribution of vegetation was mapped in the active channel and floodplain, but not on the higher elevation inactive surfaces.

Typically inactive deposits include debris fan, terrace or eolian sand. Debris fans are highly dissected and fan surfaces may include deposits of varying ages. Only 3 map units of each fan were distinguished; the most recent incised channel on the debris fan surface, the main fan surface, and the distal portion of the fan which is inundated regularly by the river. Two terrace levels were also distinguished: an intermediate terrace level characterized by mature cottonwood forests, and a higher terrace distinguished by non-riparian vegetation and developed soils.

Field Mapping-Flow Patterns and Near-shore Substrate

Surface-flow patterns and shoreline substrate were mapped to permit measurement of relationships between discharge, areas of low-velocity and recirculating flow, and distribution of shoreline habitats. Mapping occurred in the Surprise Canyon, Joe Hutch, and Coal Creek study reaches on 6 occasions between 1995 and 1997. Mapping in the Cedar Ridge reach occurred on 3 occasions in 1996 and twice during 1997. Discharges during mapping ranged from 2,100 to 27,000 ft^3/s. Flow patterns were divided into areas of downstream flow, and eddies which have zones of flow recirculation. Eddies were demarcated as the area of channel enclosed by the shoreline and the Von Karmen vortex street, generally known as an eddy fence. Areal extent of eddies was determined by obtaining a vantage reasonably high above the river from which the eddies were easily

identified and mapped. Flow characteristics within the eddies were determined from observations of flotsam from shore, or by direct inspection from an inflatable kayak.

Shorelines in each of the reaches were delineated into 6 general categories; fine-grained alluvium, densely-vegetated fine-grained alluvium, cobble and gravel, debris flow deposits, talus, and bedrock. Because of the significance to near-shore habitat, densely-vegetated fine-grained alluvium, where vegetation was inundated or overhanging the river, was mapped as a shoreline class separate from bare fines. Vegetation occurring on coarse substrates was also mapped, but because it occurred infrequently was not considered independently. The effect discharge has on the relative abundance of any given shoreline habitat type was analyzed both by individual study reach and as the summation of the 4 reaches. Lengths of each shoreline class were measured in each reach at 5 or 6 discharges ranging from 2,100 to 27,000 ft^3/s. Total lengths of each shoreline category were totaled for each reach, and divided by channel length. The resultant unit lengths of each shoreline type were plotted against discharge for each reach.

GPS

Each individual air photo was geo-referenced in the field in order to transform field maps into a continuous reach map. The coordinate position of control points on the Earth's surface was obtained using a hand-held Global Positioning System (GPS). A minimum of 4 control points were established on the first air photo of each reach, and each subsequent photo contained enough controls to overlap with previous and subsequent photos. Control points were objects that could be positively identified on the ground and photo, and were not likely to have changed since the time of the photograph. Control points were typically prominent boulders and man-made structures. GPS relies on the availability of navigation satellites within the visible sky. In narrow canyons, narrow windows of sky may contain too few satellites to calculate positions. Pathfinder software was used before mapping field trips to calculate times and locations within the canyons where abundant satellites would be visible. GPS accuracy is also influenced by a pre-

installed error in the satellite signal which limits the accuracy to ± 100 m. To eliminate this error, GPS data collected in the field were compared with data collected simultaneously at a base-station of known geographic location. The direction and magnitude of the pre-installed error was calculated and subtracted from the field data resulting in positions accurate to ± 2 m.

GIS Database Creation

Individual segments of field maps were digitized separately and entered into a GIS database using Arc/Info software. Once digitized, control points in each map segment were assigned coordinate values in Universal Transverse Mercator (UTM) units. The software was used to organize the map segments into their correct positions in space according to the coordinate values of the control points. Segments were then stitched together into one continuous reach map. Each line segment (arc) and enclosed polygon was assigned attributes according to what they represent on the map. An eddy in a flow pattern map, for example, is an enclosed polygon consisting of several arc segments. The segments were attributed as eddy fence or shoreline substrate type. The polygon itself was attributed according flow conditions such as recirculating, stagnant, or downstream flow (Fig. 4). Lengths of arcs and areas of polygons were calculated, and tables containing lengths, areas and attributes were exported into a spreadsheet application for manipulation. Final maps were created and printed using ArcView software.

Channel Cross-Sections

Twenty-two channel cross-sections were established in the 4 study reaches. Cross-sections were used to characterize channel geometry, identify bed material, help characterize geomorphic variability within and between reaches, and to establish long-term channel monitoring sites. Five to 6 cross sections were surveyed at about 1.6 km intervals within each of the 4 study reaches. These cross sections were established in 1995 at approximately bankfull discharge using a geodetic total station and depth-recording echo sounder. Cross-sections were located near river mile markers located by Belknap (1994),

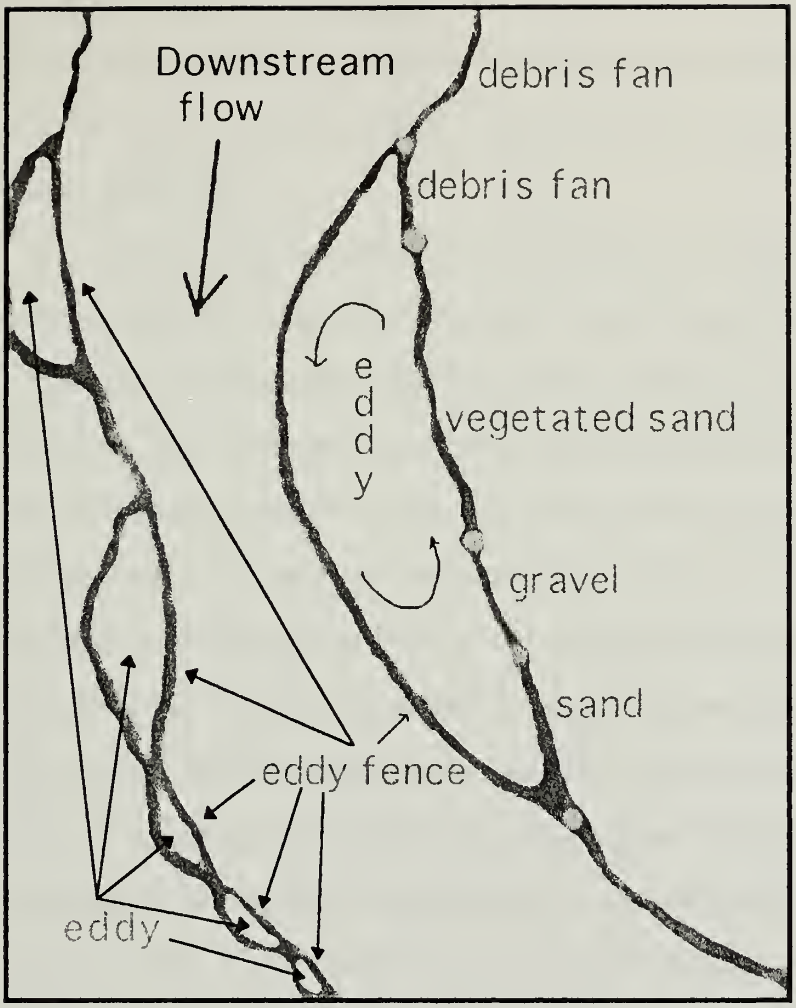


Figure 4. Example of how a habitat map is given atttibutes for use in a GIS database. In this example each line segment or arc is assigned a name describing either the bank material at the shoreline, or the division between downstream and recirculating flow (i.e. eddy fence). Areas enclosed on all sides by arcs are polygons. Polygons are given attibutes such as eddy or downstream flow. Once attributed, arc lengths and polygons areas can then be calculated and sorted by type.

so as to create a systematic sample of channel types and bed materials. Waves in rapids cause many difficulties in measuring the bed, so cross-sections were not surveyed in rapids. Cross-sections were established in small riffles, zones of strong downstream flow, pools, and eddies.

Cross-section endpoints were monumented with either rebar or fence posts which were pounded to depths such that about 10-cm are exposed above ground surface. Transects were measured by attaching a length-calibrated Kevlar tag-line to the endpoints. The total station was used to measure ground-surface elevations under the tag line as well as water-surface elevation. Depth of the bed was measured from a cataraft equipped with a paper-trace echo sounder and outboard motor. The boat operator maintained the boat carefully under the tag-line while slowly crossing the river, and a second individual measured depth and tag-line position using the echo sounder at the marked locations along the tag-line. At least 4 passes were made under the tag-line, and points in the channel were also surveyed with a total station where wading was feasible. Echo-sounder depths were compared with total station measurements to gage the accuracy of the echo-sounder. Echo-sounder measurements concurred with total station measurements and rarely deviated more than a few centimeters. Coordinate data from the total station was reduced to distance and elevations relative to endpoints. These data were combined with the average depth recorded with the echo sounder at marked points under the tagline to create a complete profile of the transect between the endpoints (Fig. 5) The standard deviation of the depths at each point was calculated and used as values for the determination of error. Errors were highest where the bed had a steep slope toward the thalweg or where boulders were on the bed. These errors are reported as the error bars on plots of cross-sections.

Photo Matching

Archival searches were conducted to locate historical oblique photos taken in Desolation and Gray Canyons which show the river and alluvial valley in past years. Once

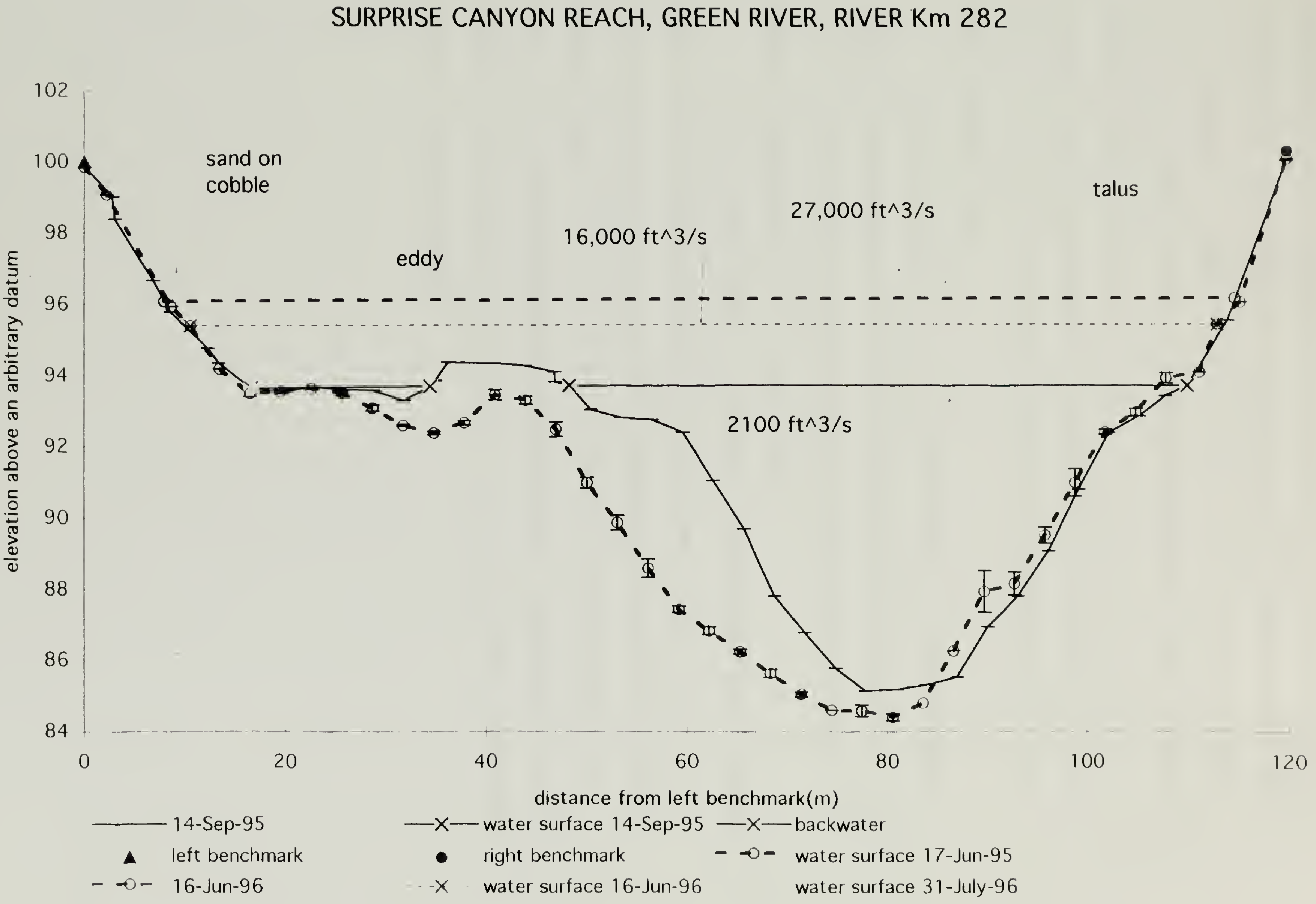

SURPRISE CANYON REACH, GREEN RIVER, RIVER Km 282
elevation above an arbitrary datum
102
100
98
96
94
92
90
88
86
84
0
20
40
60
80
100
120
distance from left benchmark(m)
sand on cobble
eddy
16,000 ft^3/s
27,000 ft^3/s
talus
2100 ft^3/s
14-Sep-95
left benchmark
16-Jun-96
water surface 14-Sep-95
right benchmark
water surface 16-Jun-96
backwater
water surface 17-Jun-95
water surface 31-July-96

Figure 5

located, the discharge at the time of photo was determined from historical gaging records so that field trips could be planned to replicate the photo at or near the same discharge.

Black-and-white images were made using a Crown Graphic 4x5 Field View Camera. Camera locations of the original photos were relocated by comparing the relative location of landmarks that appear in the photo. Once distant landmarks appeared to line up, the position of fore ground features were compared with the distant landmarks and the camera position adjusted. Once located, benchmarks were established at the camera position for future work.

In the lab, matched photos were examined for changes in riparian vegetation, evidence of channel narrowing, the number of geomorphic surfaces adjacent to the channel, and changes in the substrate composition of bars and islands. Observed changes were analyzed and summarized for each image (Appendix A).

Aerial photographs taken in 1936 (National Archives, Approx. scale; 1:12,000) and 1963 (source unavailable, approx. scale; 1:4000) were also analyzed (Table 2). When oblique photos showed evidence of a shift in some physical or vegetation condition, air photos were used to determine the timing and scale of the changing condition. For example, several oblique photos showed dramatic increases in vegetation between 1922 and 1996. The 1936 and 1963 air photos were used to determine when and where this increase in vegetation occurred.

TABLE 2. SUMMARY OF AIR PHOTO INFORMATION

AERIAL PHOTOGRAPHS

DATE	DISCHARGE ft^3/s	SCALE	SOURCE
16-Sep-1936	2260	1:12,000	National Archives
Fall or Spring 1963*	Approximately 2000 ft^3/s	1:4,000	Unknown
5-Oct-93	1950	1:5,000	Bureau of Reclamation, SLC Utah

*Dates and flight info were all cropped off these photos. Dates of photos were determined by identifying and dating a bridge which was being constructed at the time of the photos

RESULTS

Characteristics of the Alluvial Valley -- Surficial Mapping

Surficial deposits in the study reaches can be grouped into 3 categories: active channel deposits which are inundated and re-worked annually, the modern floodplain, which is inundated less frequently, and inactive surfaces which are never inundated (Fig. 3). Appendix B contains complete descriptions of map units. Debris fan material is the most abundant surficial deposit in the alluvial valleys of the three study reaches in Desolation Canyon and is a dominant deposit in the Coal Creek reach in Gray Canyon (Table 3). The majority of the surface area of these debris fans, however, is never inundated by the river. Debris fans in Desolation Canyon are typically very large and of low gradient, with the distal end sometimes spanning as much as a kilometer (Plate 1). Debris fans occupy between 36-58 percent of the entire alluvial valley in the three reaches in Desolation Canyon (Table 1). The main fan is often so large that it acts more as a meander bend than a constriction in the channel. These surfaces are typically incised by small ephemeral stream channels which, during episodic flash-floods, deliver the sediment that restricts flow and causes rapids and eddies. In the Coal Creek reach, the alluvial valley is much narrower, and as a result debris fans are typically steeper and narrower than fans in Desolation Canyon and comprise a smaller proportion of the total alluvial valley .

Alluvial terraces are the second-most abundant surficial deposit, and occupy between 10 to 16 percent of the alluvial valley. These surfaces were deposited during episodes of over-bank flooding, but are currently not inundated. Bedding planes are typically horizontal, and natural levees are common. Because they are presently not scoured by floods, woody vegetation on these surfaces is abundant and mature.

Eolian sand also makes up a fraction of surficial deposits in each of the reaches but is only substantial in Desolation Canyon. These wind blown sand deposits are consistently

TABLE 3. DISTRIBUTION OF SURFICIAL DEPOSITS IN THE ALLUVIAL VALLEYS OF THE 4 STUDY REACHES, AS A PERCENTAGE OF THE TOTAL VALLEY AREA

	ACTIVE CHANNEL AND FLOODPLAIN					INACTIVE ALLUVIUM (NOT INUNDATED UNDER MODERN CONDITIONS)			
REACH	GREEN RIVER AT BASEFLOW	FINE GRAINED ALLUVIUM	GRAVEL	DEBRIS FLOW	TALUS	TERRACE	INACTIVE DEBRIS FAN	ACTIVE DEBRIS FAN	EOLIAN SAND
CEDAR RIDGE	28.5	4.6	2.1	1.5	0.4	15.6	40.8	2.9	3.5
SURPRISE	28.3	5.3	3.4	2.1	0.9	13.0	34.1	1.7	11.1
JOE HUTCH	19.0	5.8	4.0	1.2	0.5	10.1	53.9	3.2	2.1
COAL CREEK	53.8	7.8	4.6	3.1	2.5	14.4	12.5	1.1	0.1

located near large recirculating eddies. At low discharges, newly-created sandbars formed by these eddies are exposed and are the source material for these wind-blown deposits. Eolian dunes in Desolation Canyon can exceed 5 m in height and are often vegetated with grasses and desert shrubs. Although Gray Canyon contains abundant sandbars, eolian dunes are limited by the lack of surface area in the narrow canyon, and few exist.

The modern active channel and its floodplain, are inset within the inactive portion of the alluvial valley. The active channel and modern floodplain combined occupy between 30 and 70 percent of the alluvial valley floor (Table 3). The floodplain, and the portion of the active channel exposed at baseflow, are referred to as the banks of the river in this report. Bank-material is composed of fine-grained alluvium, gravel and cobbles, fine to coarse-grained debris flow material derived from tributaries, scree that occurs as talus on the lower part of hillslopes, and bedrock. Where tributary-derived debris partially blocks the channel, rapids typically occur. Downstream from these rapids, recirculating eddies are often present, and fine-grained alluvium, in the form of sand bars, occurs in these areas. Some of the coarse material delivered by tributaries has been reworked and transported downstream creating abundant cobble bars and gravely banks in the reaches immediately below rapids. Schmidt and Rubin (1995) called this assemblage of geomorphic features a fan-eddy complex. Upstream from the constriction, pools form, and fine-grained terrace-like deposits line the margins of the channel. These deposits are the modern floodplain and are often densely vegetated with willow and tamarisk. Bedding surfaces observed in these deposits are predominantly horizontal, indicating deposition through vertical accretion.

Despite the predominance of debris-fan material in the alluvial valley, bank material in the 4 study reaches is dominated by fine-grained alluvium (Fig. 6). Riparian vegetation is abundant along the channel margins and occurs predominantly on these fine-grained deposits. Eddy associated sandbars are lower in elevation than the floodplain and are subjected to frequent scouring and are typically less densely vegetated than channel margin sands or floodplain surfaces. Vegetation occurs on other substrate types to a lesser degree,

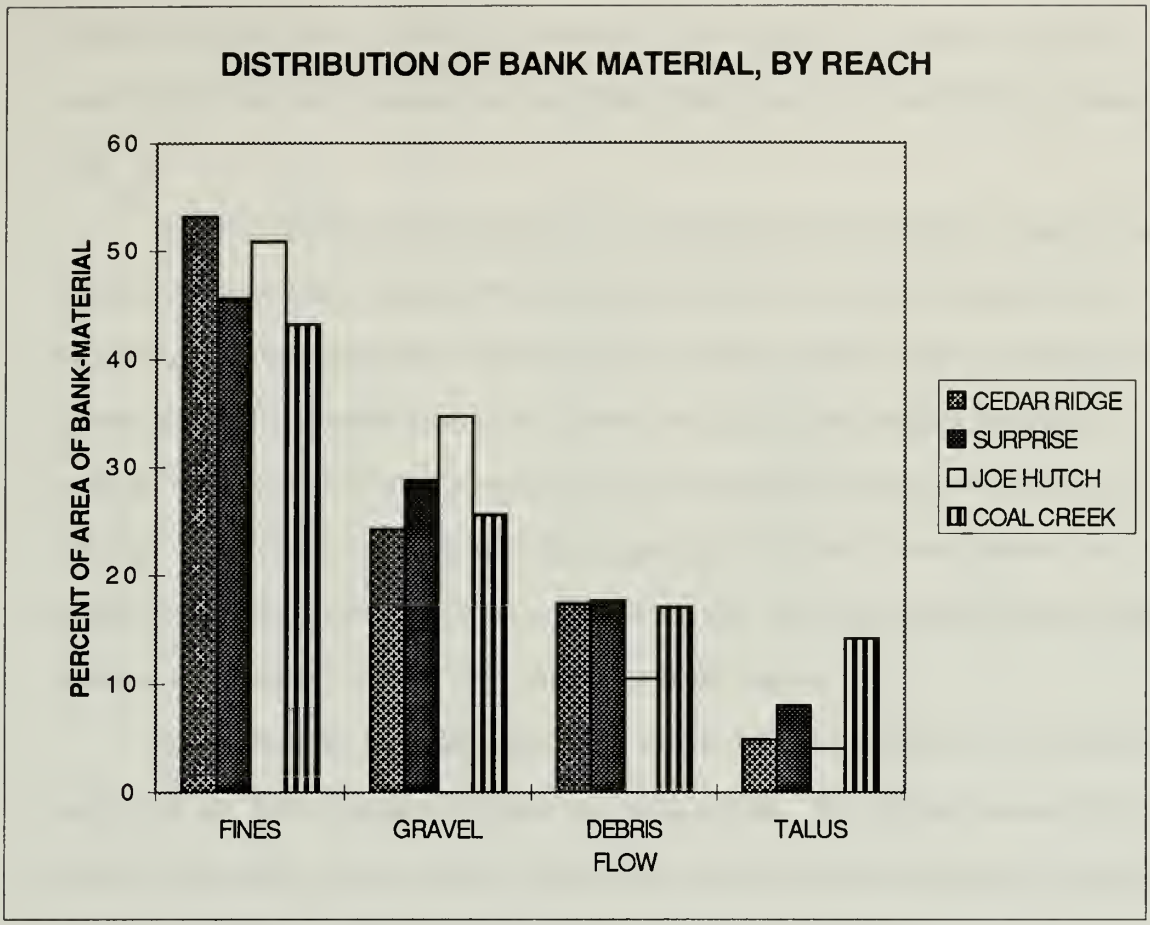


Figure 6. Graph shows the general distribution of different bank materials in the 4 study reaches. Bank material includes alluvium in the active channel exposed at baseflow, and the modern floodplain.

and was least abundant on debris fan material where vegetation is subjected to both scouring from the main channel and intermittent flash floods from the tributary channel (Fig. 7).

Cobble and gravel bars typically occur downstream from debris fan deposits and in many cases show a downstream gradation with clasts becoming more rounded with increasing distance downstream from the tributary source. Pebble counts conducted on the upstream end of 15 representative cobble bars show grain sizes ranging from fines to particles as large as 1024 mm, with d_{50} particle sizes typically between 45 and 64 mm. Cobbles are generally well rounded and are typically imbricated. These deposits are generally located at lower elevations in the channel and frequently grade into fine-grained deposits as one moves laterally from the center of the channel.

Talus which has been deposited in the active channel is comprised of angular blocks ranging in size from several centimeters to several meters. The irregular shape of talus deposits frequently creates numerous small eddies wherein small sandbars are deposited along the shorelines. Large interstitial spaces exist within the talus.

Surficial geologic maps of the alluvial valley in the 4 study reaches are included with this report as Plates 1-4. These maps show the distribution of alluvium within the alluvial valley, as well as the areal extent of the river at baseflow conditions, and the lateral extent of the alluvial valley. These maps also show the distribution of riparian vegetation within the active channel and modern floodplain.

Plate 1 shows the Cedar Ridge study reach and shows a very broad alluvial valley dominated by inactive debris fan surfaces. The debris fans in this reach are some of the largest in Desolation Canyon and probably rank among the largest in the Green River system. Although large, these fans have a very low gradient and only three -- Big Canyon, Firewater Canyon, and Cedar Ridge Canyon -- now deliver enough coarse debris to the river to form small rapids. Despite the abundant debris fan material, the dominant bank material is fine-grained alluvium, followed by gravel and cobbles. Cobble bars and eddy-

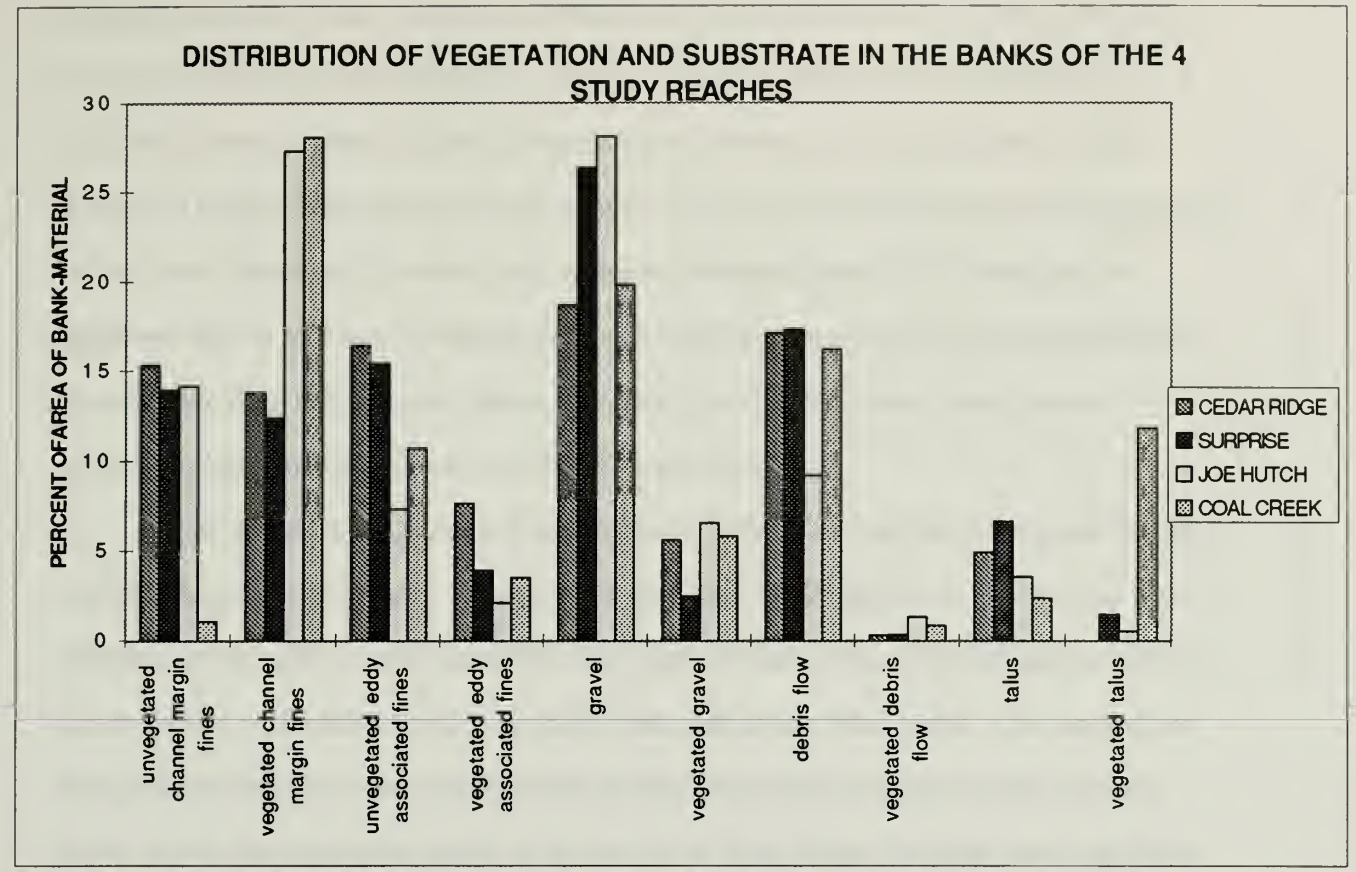


Figure 7. Graph shows distribution of vegetation and substrates as a percentage of bank material exposed at baseflow discharge. Vegetation occurs predominantly on fine-grained alluvium and is more abundant on channel-margin fines than on eddy deposited fines.

deposited sand bars occur below constrictions in the channel caused by these debris fans. The active channel is lined mostly by vegetated channel-margin fine-grained alluvium. A large mid-channel island is located at the extreme downstream end of this reach. This island is a large cobble bar overlain by a layer of sand, as is every major mid-channel island in the 4 study reaches. The sand layer varies in thickness, from a thin veneer on the upstream end, to as much as several meters on the downstream end. On several of these islands, including this one, the highest elevation deposits are terraces with mature cottonwood galleries and show no signs of recent inundation.

Plate 2 depicts the Surprise Canyon reach. Debris fan material is the predominant surficial deposit in this reach. However, the dominant bank material in this reach is fine-grained alluvium, but coarse shorelines are abundant, and the shorelines of the river are in direct contact with bedrock and talus more often than in any other reach. The majority of fine-grained alluvium in this reach occurs as eddy -deposited sandbars located directly below debris-fan controlled rapids at the mouths of Steer Ridge, Surprise, and Log Cabin Canyons.

Plate 3 shows the alluvial valley of the Joe Hutch study reach. The alluvial valley in this reach is the widest of the 4 study reaches. Debris flow material is the dominant surficial deposit, as in the Cedar Ridge and Surprise Canyon reaches, and fine-grained alluvium is the most abundant substrate in the banks of the channel. Gravel shorelines, however, are more predominant here than in the other reaches. There are several secondary channels in this reach which are dry at baseflow but inundated at discharges around 7000ft^3/s. Such is the case with the pair of islands just above Joe Hutch Canyon. There is also an abandoned secondary channel in this reach, located near Florence Creek. The abandoned secondary channel, identified as the cottonwood terrace, surrounds an even higher terrace level. This secondary channel shows signs of historic inundation and was likely abandoned due to climate-related decreases in flood magnitudes that occurred in the 1930s.

Plate 4 shows the alluvial valley of the Coal Creek study reach. This reach occurs in Gray Canyon and is much narrower than the 3 upstream reaches. The river is narrowly confined by bedrock cliffs and occupies over 50 percent of the valley during baseflow conditions. A thin, densely vegetated terrace lines the channel through most of the reach and is the dominant surficial deposit. Talus sloughed from the nearby cliffs is abundant and often overlain by a veneer of vegetated fine-grained alluvium. Unvegetated sand and gravel bars are rare in this reach and occur almost exclusively below the mouths of Coal Creek and Poverty Canyon, where debris flows deliver abundant coarse material to the river.

Channel Geometry

The channel in each study reach is confined to varying degrees depending on local bedrock geology and the relative abundance of bedrock, debris flow material, and talus in contact with the channel. The channel is typically partly confined by bedrock, but more of the channel is confined by talus or coarse debris flow deposits (Table 4). The degree of confinement is reflected in measurements of width/depth ratios of the channel, average channel widths and average alluvial valley widths (Tables 1 and 5). The Coal Creek reach is the most confined, followed by the Surprise and Cedar Ridge reaches. The two most constricted reaches, Surprise Canyon and Coal Creek, lie within the highly resistant Wasatch and Mesa Verde sandstones. Bedrock in the Cedar Ridge and Joe Hutch reaches is a mix of sandstone, siltstones, and shales.

Bed material at established cross-sections is predominantly sand and gravel, but ranges in size from silt to large angular boulders. The range of annual fluctuations in bed elevation was determined by resurveys of the cross-sections. As expected, the range of scour and fill is greatest where the bed is sand, but bed elevation changes occur even over gravel beds. Channel cross-sections with the coarsest beds had the narrowest channel widths and had the least annual change in bed elevation. Evidence of dunes at high discharge was detected at several cross-sections from uneven bathymetric traces which did

TABLE 4. BANK MATERIAL AT THE SHORELINE AT BANKFULL DISCHARGE, AS A PERCENTAGE OF TOTAL SHORELINE LENGTH

STUDY REACH	BEDROCK	TALUS	DEBRIS-FAN	GRAVEL	FINE-GRAINED
CEDAR RIDGE	4	12	8	4	72
SURPRISE	13	22	19	16	30
JOE HUTCH	3	17	13	21	46
COAL CREEK	14	29	9	4	44

TABLE 5. SUMMARY OF WIDTH/DEPTH RATIOS AND BED MATERIAL AT MEASURED CROSS-SECTIONS

				BED MATERIAL		
STUDY REACH	NUMBER OF CROSS SECTIONS	AVERAGE WIDTH/DEPTH RATIO	RANGE OF WIDTH/DEPTH RATIOS	SAND	GRAVEL	BOULDER
CEDAR RIDGE	5	49	73-29	3	2	
SURPRISE	6	30	42-19	2	2	2
JOE HUTCH	6	48	73-21	1	4	1
COAL CREEK	5	33	49-16	1	3	1

not exist at base-flow (Fig. 8). Aggradation of the thalweg in cobble-bedded transects at high discharge, also showed that the bed material was moving in these reaches (Fig. 9). Sand-bedded cross-sections experienced scour and fill at high and low discharges. The greatest channel depths were measured in the 2 narrowest reaches (Surprise and Coal Creek), adjacent to zones of recirculation where thalweg depths were as deep as 13 m at approximately bankfull discharge.

Evidence of Channel Narrowing -- Historic Photo Matching

USGS photos taken in 1917 and 1922 were the primary source for historic photos (Appendix B). These photos pre-date the invasion of tamarisk and show broad channels with abundant low-elevation sand and cobble bars which are free from vegetation and appear to be unstable surfaces (Figs. 10a,11a,12a,13a). Matched photos taken in 1995 and 1996 (Figs. 10b,11b,12b,13b) show a dramatic increase in riparian vegetation, especially in tamarisk, but also in cottonwood (*Populus* sp.), box elder (*Acer negundo*), and willow (*Salix* sp.). Unstable channel-margin and mid-channel sand and cobble-bars in the early photos now have stabilized, forming vegetated floodplains, terraces and mid-channel islands. Field investigations show that 2 distinct surfaces exist in areas where vegetation has established since the 1920s. The lower surface is the modern floodplain and is vegetated predominantly by willow and small tamarisk (Fig. 14). We refer to the higher surface as the cottonwood terrace. This surface is inactive and is characterized by mature stands of cottonwood, box elder, and tamarisk trees, which show signs of having been buried in vertically-accreted alluvium. This deposit is typically less than 1 m higher than the modern floodplain surface and has evidence of historic inundation such as sawn logs in drift piles, and the absence of cryptobiotic crusts. An abandoned floodplain occurs higher than the cottonwood terrace and is referred to as the high terrace. This surface shows no

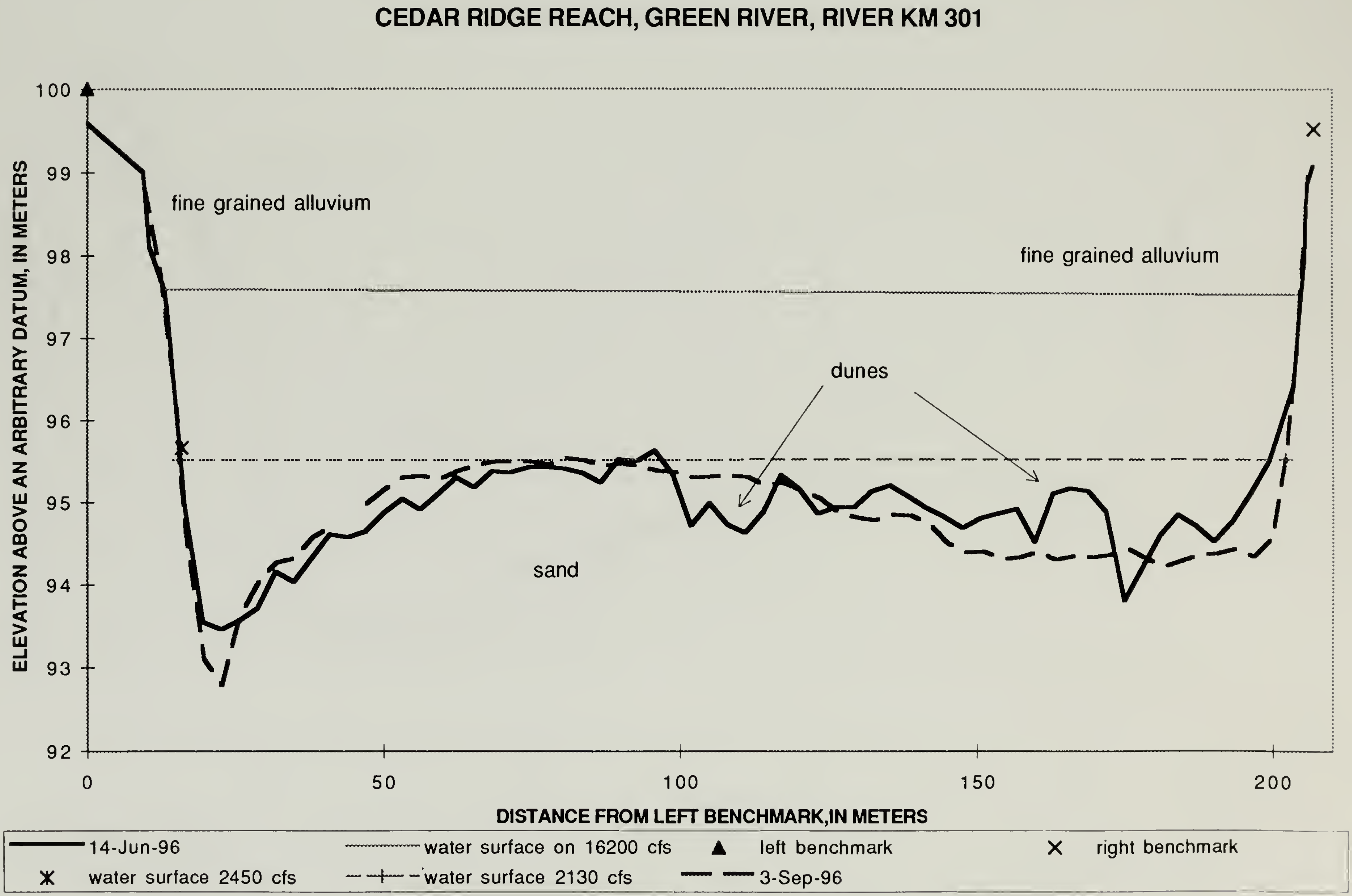

CEDAR RIDGE REACH, GREEN RIVER, RIVER KM 301
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
100
99
98
97
96
95
94
93
92
0
50
100
150
200
DISTANCE FROM LEFT BENCHMARK,IN METERS
fine grained alluvium
fine grained alluvium
dunes
sand
14-Jun-96
water surface on 16200 cfs
left benchmark
right benchmark
water surface 2450 cfs
water surface 2130 cfs
3-Sep-96

Figure 8

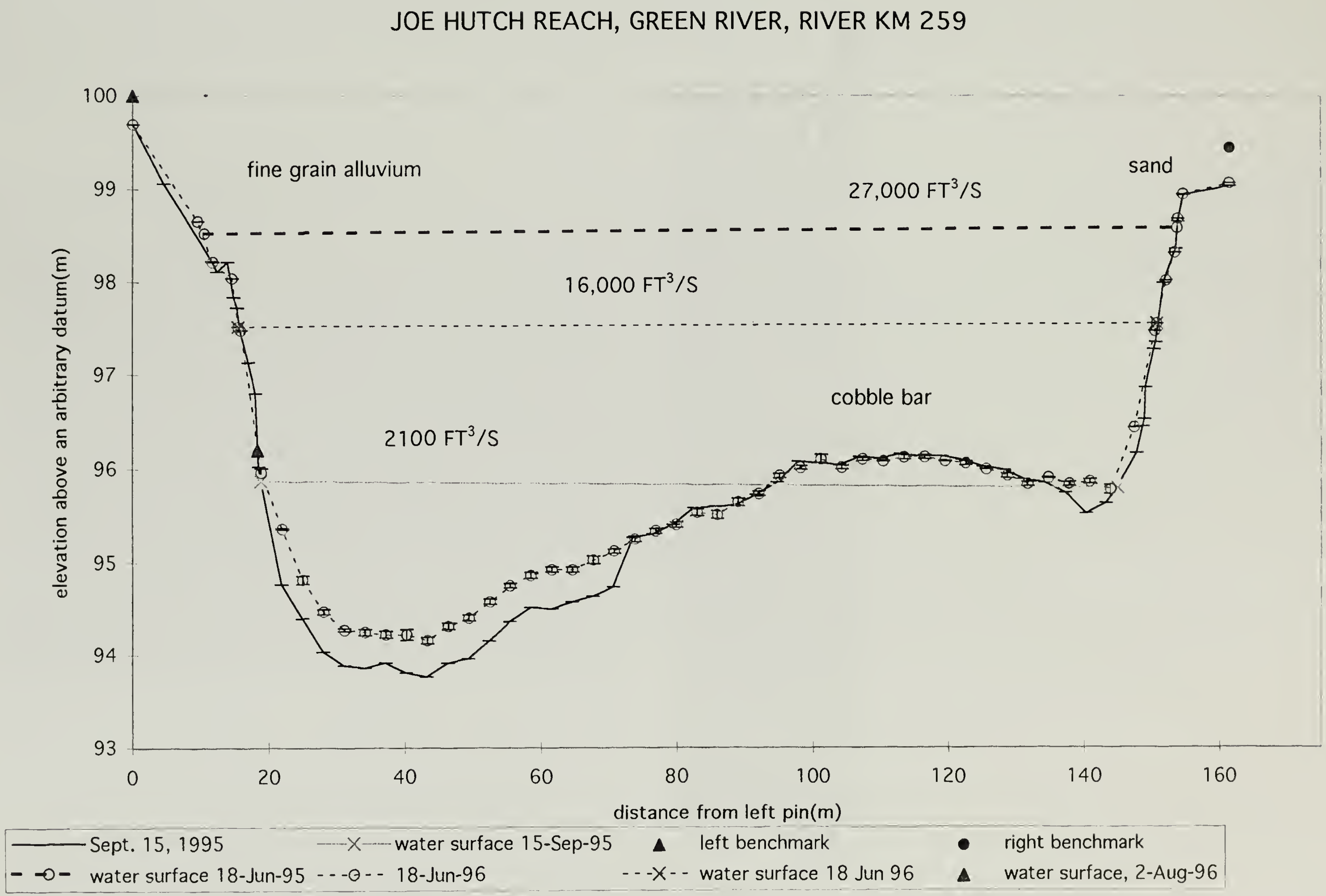

JOE HUTCH REACH, GREEN RIVER, RIVER KM 259
elevation above an arbitrary datum(m)
100
99
98
97
96
95
94
93
0
20
40
60
80
100
120
140
160
distance from left pin(m)
fine grain alluvium
sand
27,000 FT³/S
16,000 FT³/S
2100 FT³/S
cobble bar
Sept. 15, 1995
water surface 15-Sep-95
left benchmark
right benchmark
water surface 18-Jun-95
18-Jun-96
water surface 18 Jun 96
water surface, 2-Aug-96

Figure 9

Figures 10a and 10b. View are looking upstream from river kilometer 292.4. Figure 10a shows the active channel in 1922 and pictures mid-channel and channel-margin sandbars which are unvegetated, and appear to have been recently scoured. Figure 10b was taken in 1996 and shows a substantial increase in vegetation on surfaces which were part of the active channel in 1922. The mid-channel bar pictured in figure 10a has completely stabilized and now has a cottonwood terrace surface which is no longer inundated by the river. The channel margin bar on the left of the views has also become vegetated. This surface represents the modern floodplain.

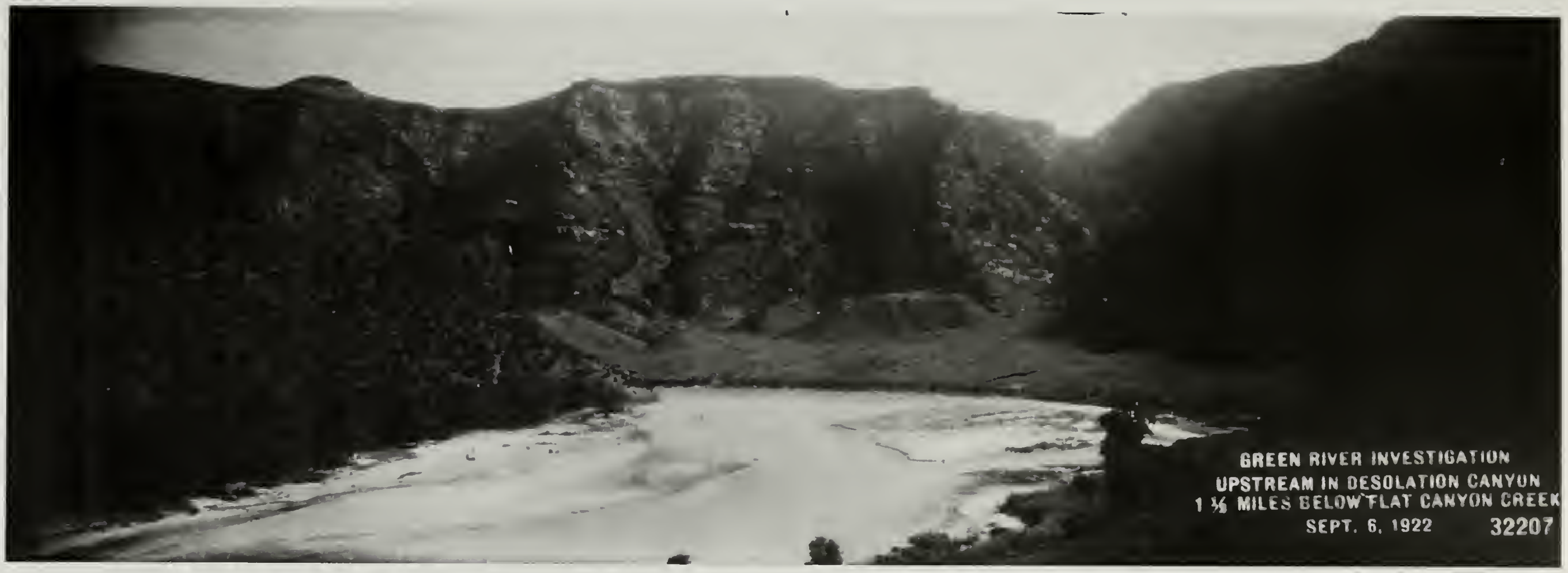

GREEN RIVER INVESTIGATION
UPSTREAM IN DESOLATION CANYON
1 ½ MILES BELOW FLAT CANYON CREEK
SEPT. 6, 1922
32207

Figure 10a

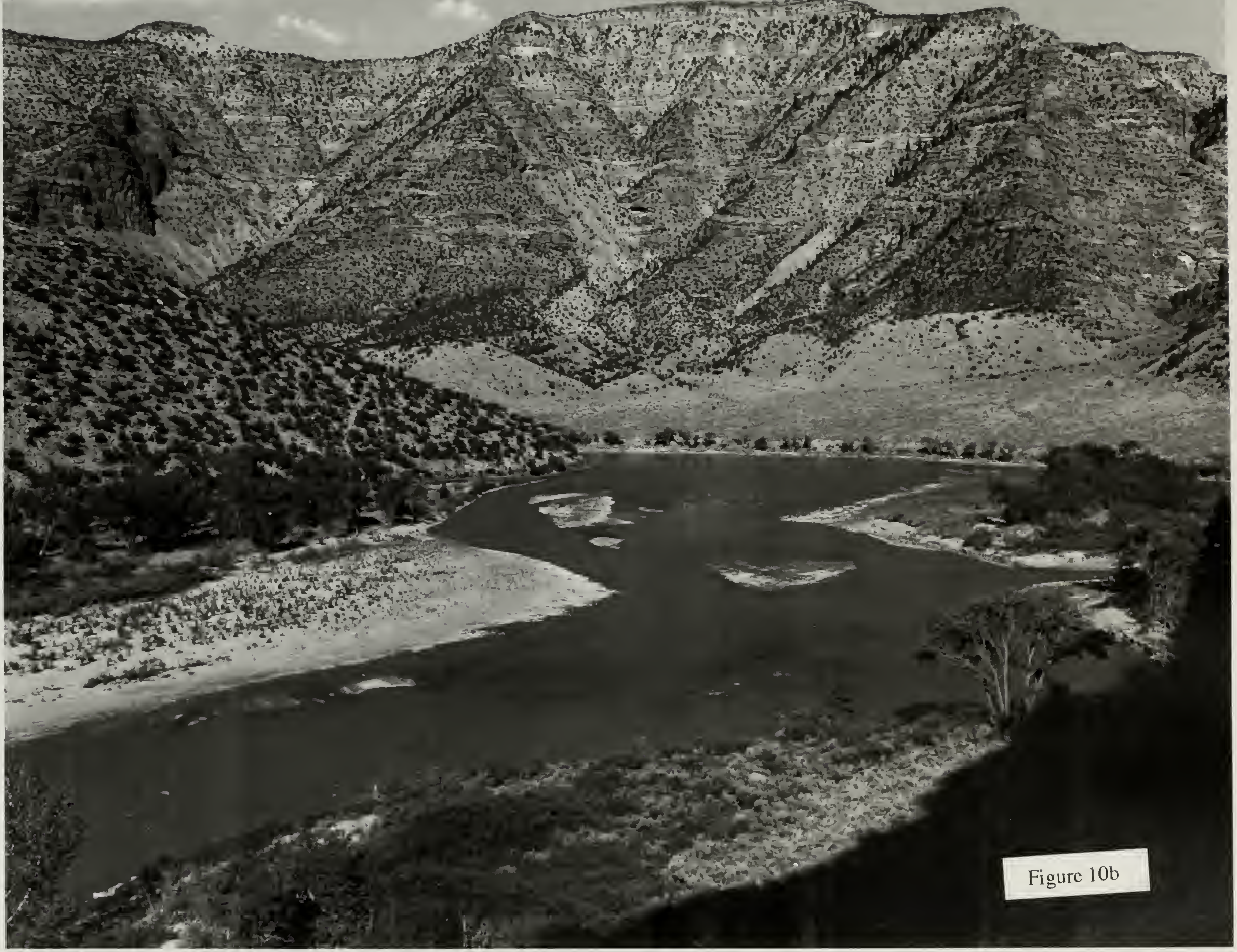
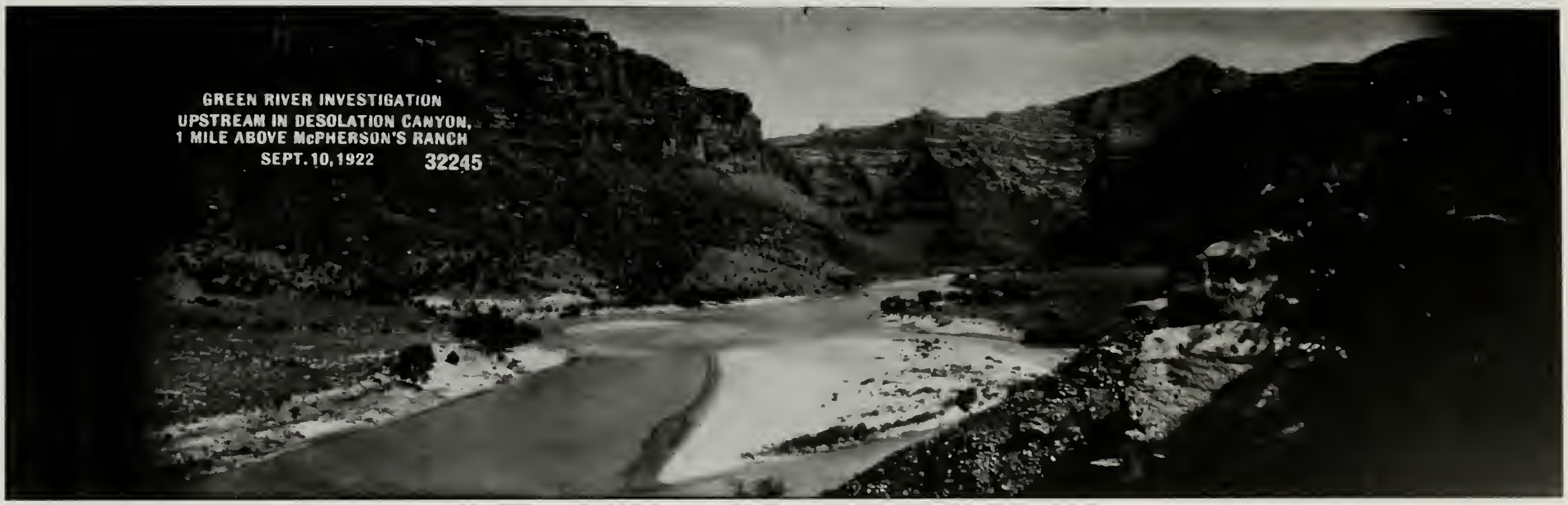


Figure 10b

Figures 11a and 11b. Views are looking upstream from river kilometer 259.3 near Joe Hutch Canyon. Figure 11a was taken in 1922 and shows 2 low-elevation mid-channel sandbars. The upstream bar is devoid of vegetation and the downstream bar is sparsely vegetated. Figure 11b was taken in 1996. Both islands are now densely vegetated. The upstream island is vegetated by a very dense stand of willow and was completely inundated by the 27,000 ft^3/s flows that occurred during this study. This surface represents the modern floodplain. The downstream island now has a cottonwood terrace and was not completely inundated at 27,000 ft^3/s. The secondary channel around this island is choked with dense willow growth. The island is becoming attached to the bank as this secondary channel becomes abandoned.



GREEN RIVER INVESTIGATION
UPSTREAM IN DESOLATION CANYON,
1 MILE ABOVE McPHERSON'S RANCH
SEPT. 10, 1922 32245

Figure 11a

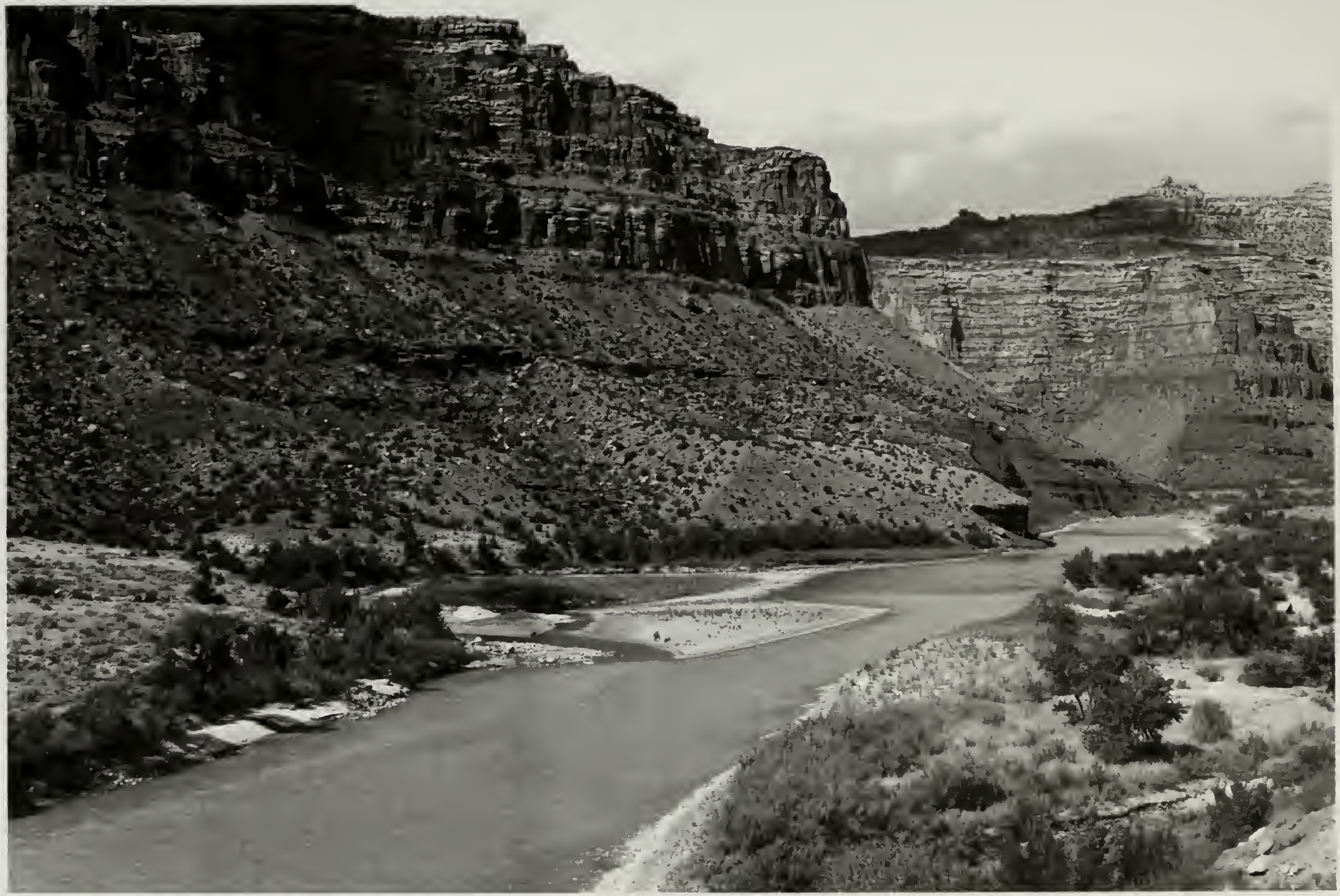


Figure 11b

Figure 12a and 12b. Views are upstream from river kilometer 273 near Three Canyon Creek. Figure 12a shows the channel margins are sparsely vegetated with cottonwood and box elder trees. At the bottom of figure 12b the 2 new surfaces that have established since 1922 are evident. Directly adjacent to the channel is a low-elevation surface with dense willows. This is the modern floodplain. Next to the floodplain is a higher elevation surface vegetated by box elder tamarisk and cottonwood trees. This is the cottonwood terrace.

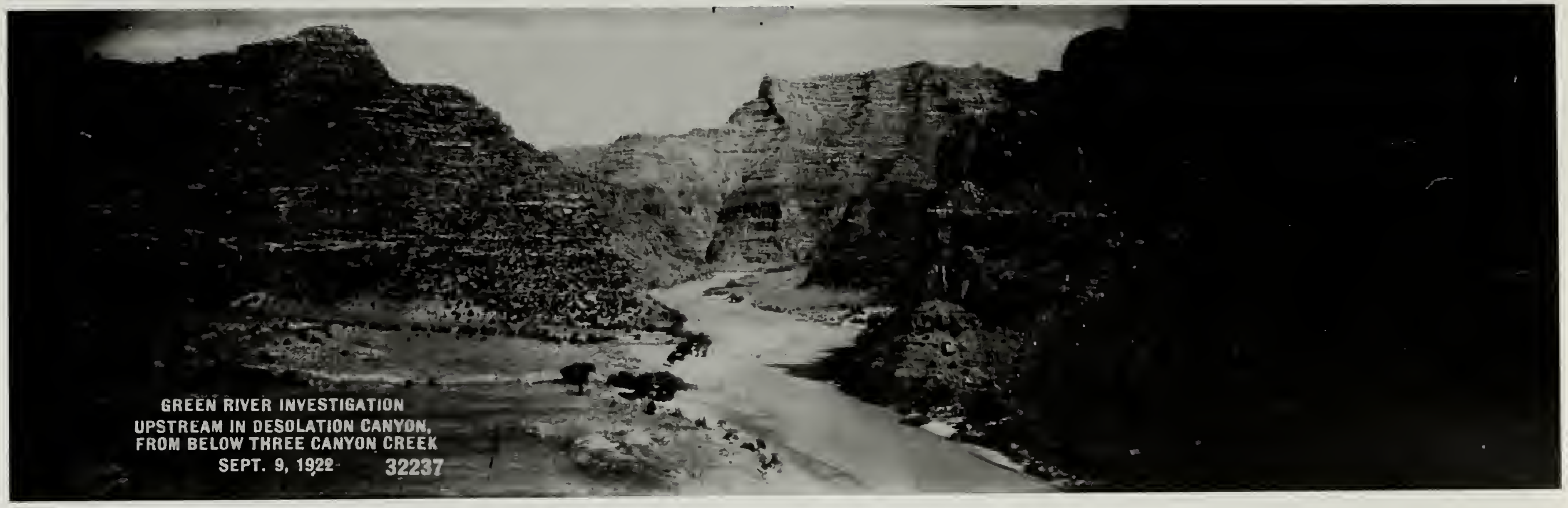

GREEN RIVER INVESTIGATION
UPSTREAM IN DESOLATION CANYON,
FROM BELOW THREE CANYON CREEK
SEPT. 9, 1922
32237

Figure 12a

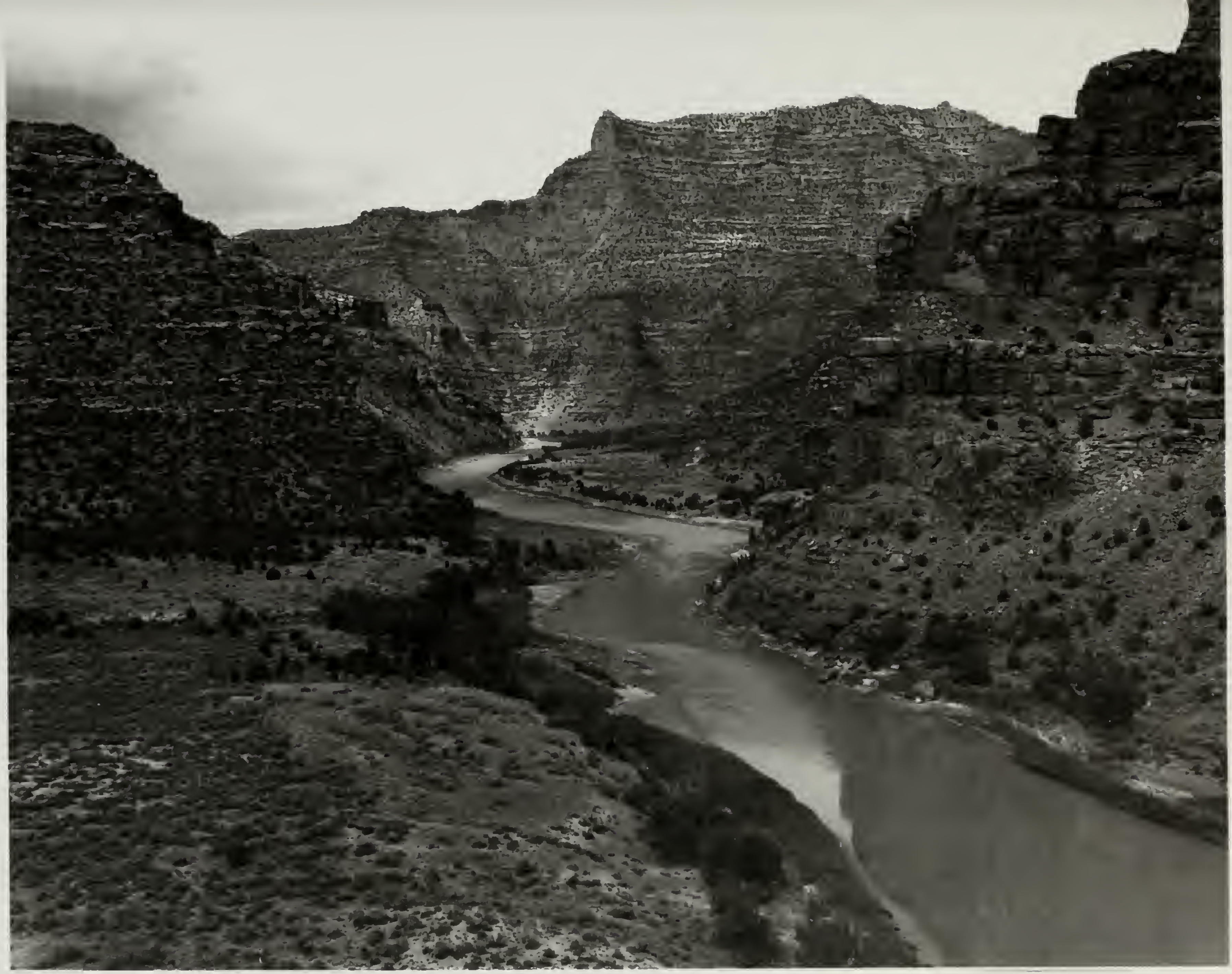


Figure 12b

Figures 13a and 13b. View is upstream from river kilometer 257, near McPhearson's Ranch. Figure 13a shows a broad unvegetated channel-margin sand/cobble bar that extends to a higher elevation stand of cottonwood trees. Figure 13b shows the bar has been colonized by a dense growth of small tamarisk trees. The bar is now a floodplain, and the active channel has narrowed considerably.

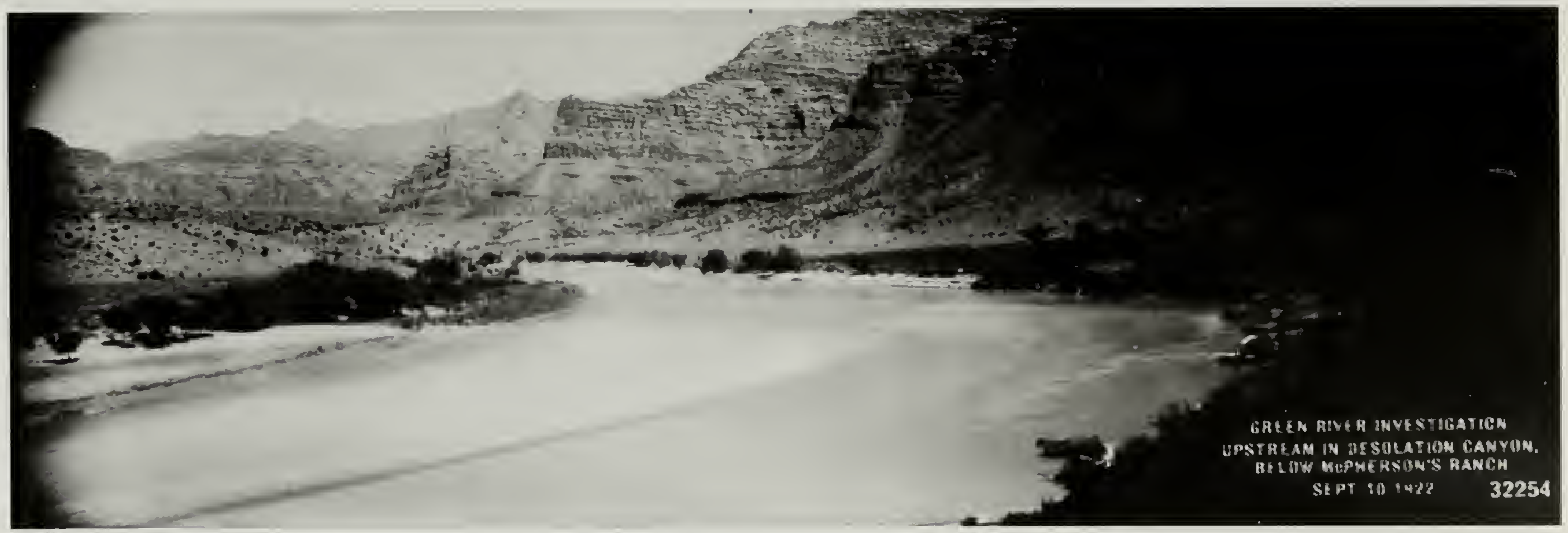

GREEN RIVER INVESTIGATION
UPSTREAM IN DESOLATION CANYON,
BELOW McPHERSON'S RANCH
SEPT 10 1922
32254

Figure 13a

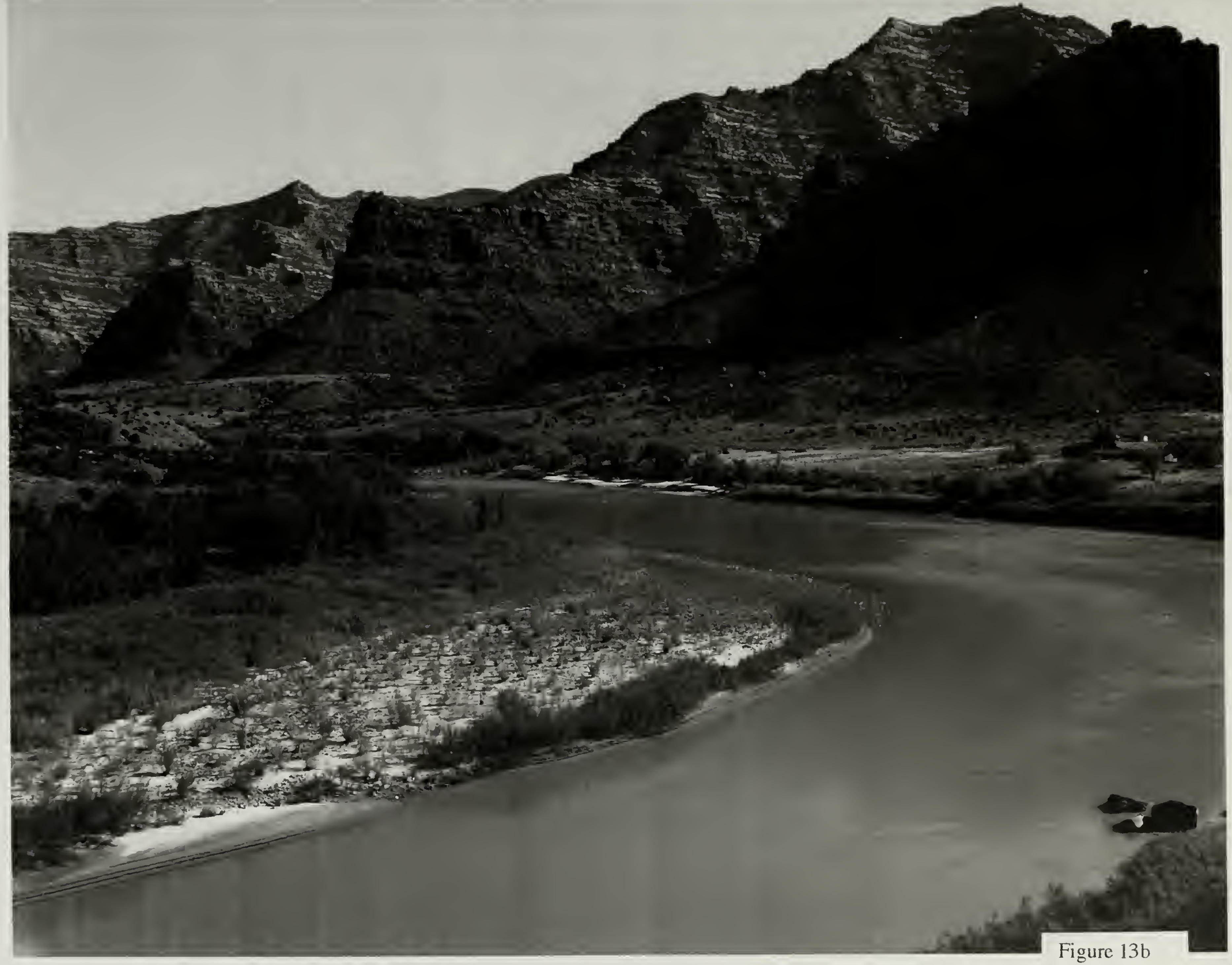


Figure 13b

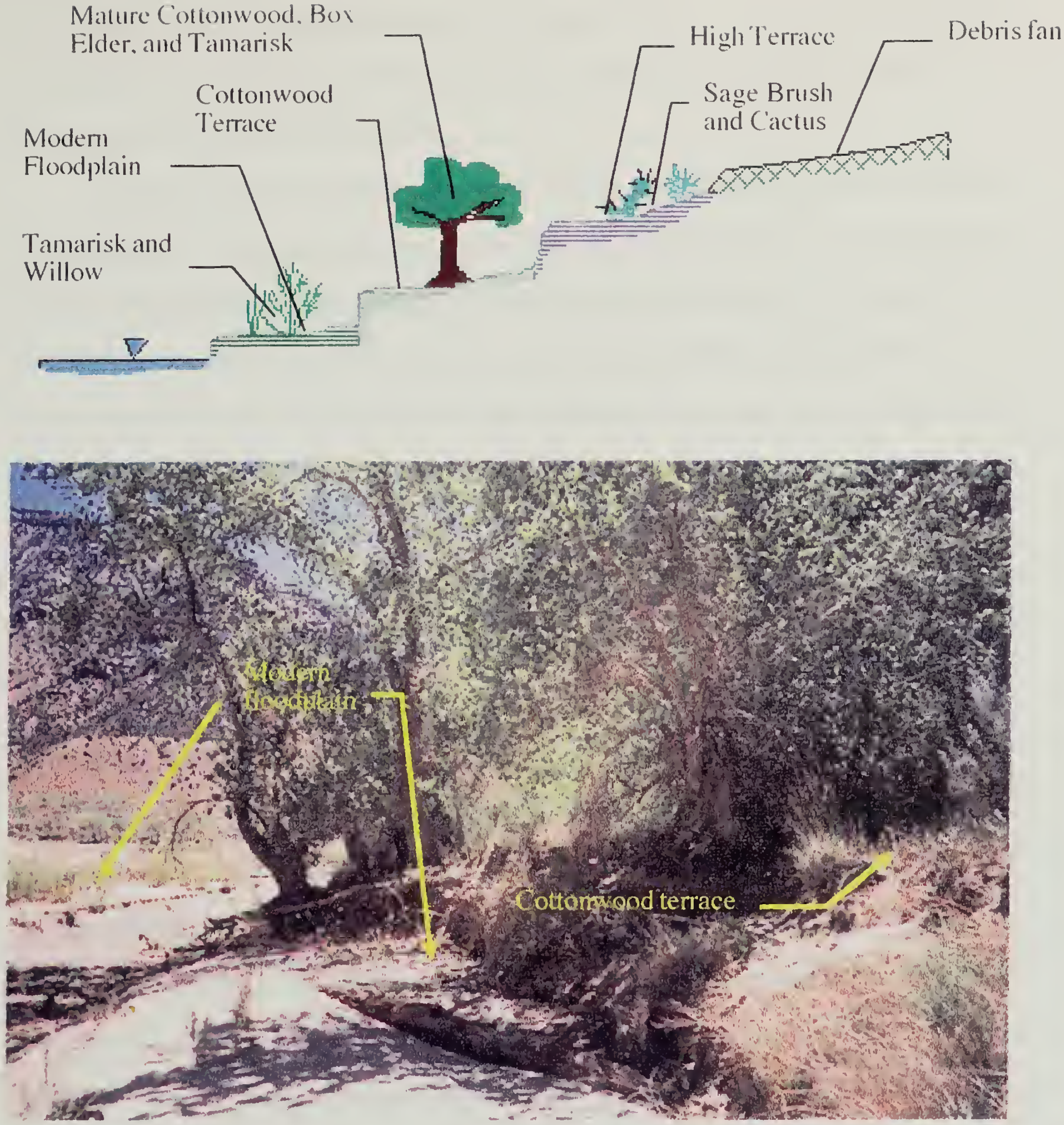


Figure 14. Two distinct surfaces have formed in Desolation and Gray Canyons in response to decreased flood magnitudes; the cottonwood terrace in response to a climatic shift in the late 1920s, and the modern floodplain in response to the closure of Flaming Gorge Dam in 1962. The photo is of the river right side of the mid-channel bar near Dripping Springs, RK (292) pictured in figures 10a and b. View is upstream. Despite the presence of tamarisk in the canyon, this surface is predominantly vegetated by new cottonwood growth that established after 1922. The lower surface, the modern floodplain, established after 1962 and is vegetated predominately with willow and young tamarisk.

sign of historic inundation, is vegetated by non-riparian species such as pinon and juniper trees, has well-developed cryptobiotic soils and, in stratigraphic exposures, is often intertounged with debris flow material.

There is strong evidence that the cottonwood terrace surface has stabilized during the past century. Oblique photos taken in 1922 by the USGS and matched in 1996, show that areas of the active channel, which in 1922 were channel-margin or mid-channel sand/cobble bars, are now part of the cottonwood terrace, vegetated with mature cottonwood, box elder, and tamarisk. Figures 10a and 11a were taken at Dripping Springs RK(292.4) and near Joe Hutch Canyon RK(259.3). The view in both photos is upstream and shows broad low-lying sandbars which are sparsely vegetated and appear to have been recently scoured. The same 2 islands (Fig. 10b and 11b) are now inactive and are vegetated by mature cottonwood, box elder, and tamarisk, as well as abundant non-riparian shrubs.

The timing of the transformation from active alluvium to abandoned terrace can be inferred by comparing other photos of these sites taken between 1922 and 1996. Aerial photographs taken of the same 2 islands in 1936 show a substantial increase in vegetation occurred between 1922 and 1936. This indicates that the surface that now occurs as the cottonwood terrace began to stabilize between 1922 and 1936 (Fig. 15 and 16). Graf (1978), estimated that after its introduction in the late 1800s, tamarisk spread upstream at the rate of 20 km/yr and that it had reached the town of Green River by 1931. At that rate, tamarisk would have spread through all four study reaches by 1936. Thus, at least some of the increased vegetation evident in the 1936 air-photos is probably due to the invasion of tamarisk.

By 1963, 1 yr following the closure of Flaming Gorge Dam, air photos show that the areal extent of vegetation at both Dripping Springs and Joe Hutch Canyon had increased only slightly since 1936. The islands, however, are densely vegetated, and appear to have inactive surfaces. Excavations of several mature tamarisk trees from the islands pictured in

figures 10a,b and 11a,b show root crowns located at a depth of approximately 0.8 m indicating that deposition has occurred since plant germination. Tree ring analysis of the 2 tamarisks excavated on the Dripping Springs island and the island near Joe Hutch Canyon, show that germination occurred around 1954 and 1949 respectively.

Between 1963 and 1993, the areal extent of vegetation in the channel increased substantially. The area where this new colonization has occurred is on what is now the active floodplain. The substantial increases in vegetation between 1922 and 1936 and between 1963 and 1993, and the small increases between 1936 and 1963, suggest there may be 2 episodes of channel narrowing, the first represented by the cottonwood terrace and the second by the active floodplain. The establishment of both surfaces is associated with decreases in flood magnitudes. Annual peak discharges decreased markedly in the early 1930s and remained low through the late 1940s (Fig. 17). The decreased flood magnitudes allowed low-elevation deposits to become colonized by tamarisk, cottonwood, and willow which facilitated the formation of the cottonwood terrace.

In the early 1960s, while Flaming Gorge Dam was filling, annual flood magnitudes decreased again and have remained on average lower than floods during the period between 1930 and 1960 (Table 6). These lower flood magnitudes allowed the colonization and stabilization of the modern floodplain. The floodplain surface is presently densely vegetated by small tamarisk and dense willow thickets, and is inundated less frequently than active deposits. Dense homogeneous stands of willow are abundant on this surface, again suggesting that decreased flood magnitudes create favorable conditions for establishment of woody vegetation, and that the stabilization of this surface is not solely a response to tamarisk. Bedding surfaces in this deposit are predominantly horizontal indicating the surface is accumulating sediment through vertical accretion. It is reasonable to assume that under current flow regimes, this surface will continue to accumulate sediment until it becomes high enough that it is no longer inundated by frequently occurring low magnitude floods, as it is now.

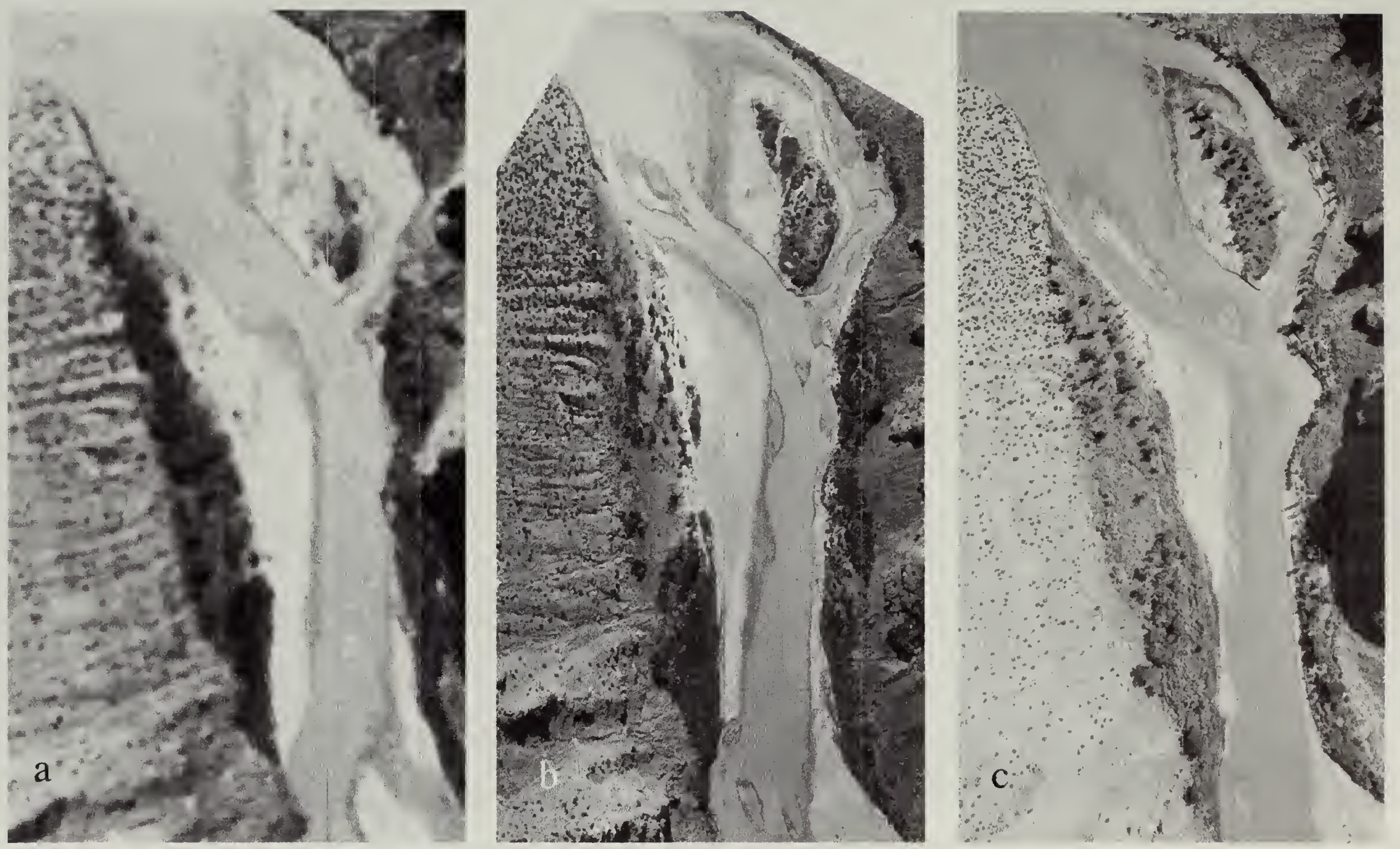


Figure 15. Air-photos of the Green River in Desolation canyon near Dripping Springs, river kilometer 292. Flow is toward the bottom of the page. Photos **a**, **b**, and **c** were taken in 1936, 1963 and 1993 respectively. Oblique photos taken of this island show that in 1922, this surface was only sparsely vegetated and appears to have been recently scoured (figure 10a). Decreased flood magnitudes during the late 1920s allowed the amount of vegetation on the island to increase sharply by 1936(Photo **a**). By 1963 (photo **b**) the island is no longer an active surface and is vegetated by cottonwood and box elder trees. Decreases in flood magnitudes after the closure of Flaming Gorge Dam allowed vegetation to become established lower in the channel, increasing the area of the island that is stable (note the dark band of new vegetation on the upstream end of the island, and increased vegetation on the sandbar below the island (photo c)).

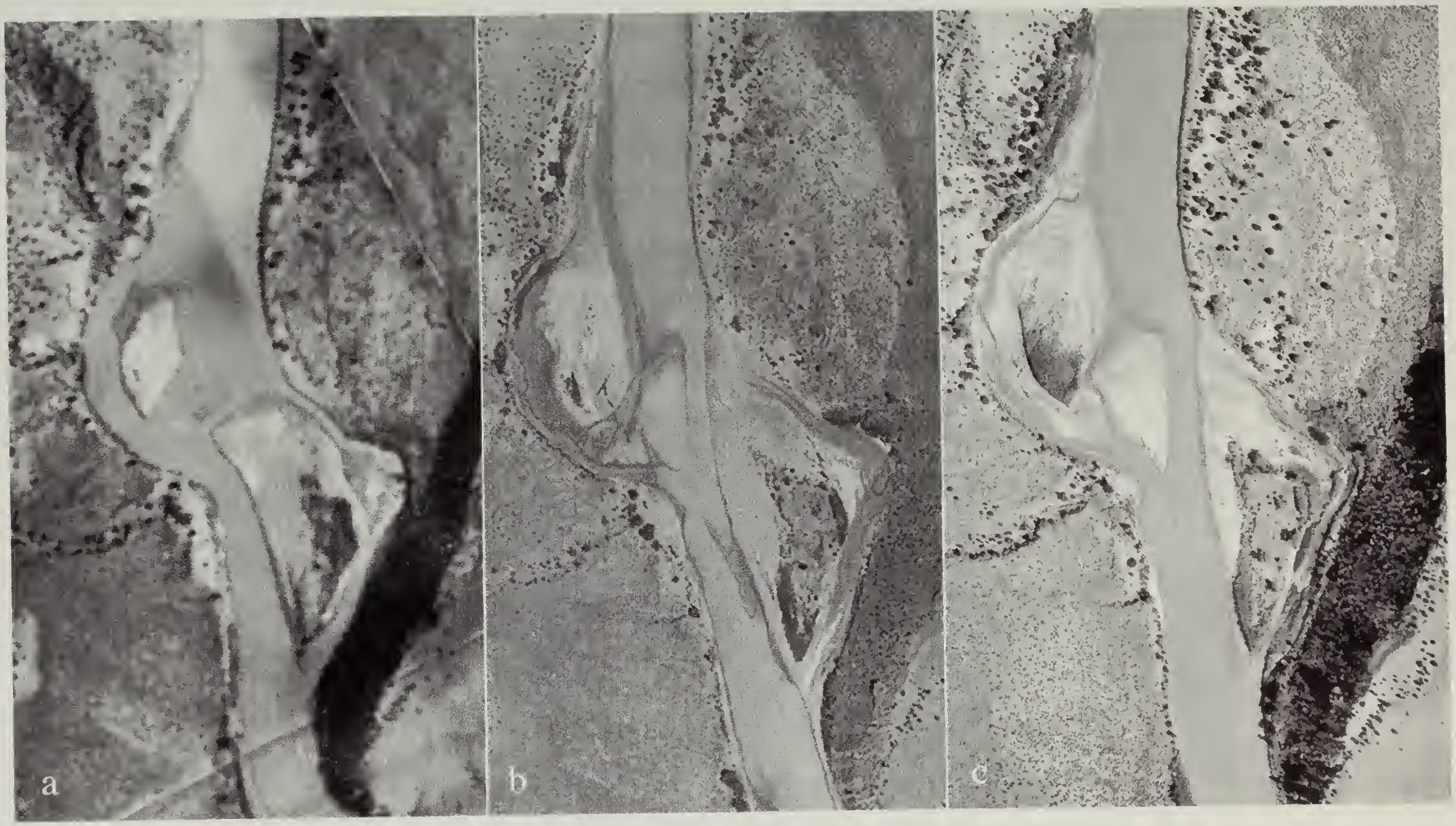


Figure 16. Air-photos of the Green River in Desolation canyon near Joe Hutch canyon, river kilometer 259. Flow is toward the bottom of the page. Photos **a**, **b**, and **c** were taken in 1936, 1963 and 1993 respectively. Decreased flood magnitudes during the late 1920s allowed the establishment of vegetation on the lower island in photo **a** (compare with figure 11a which is an oblique view of the same island in 1922). This surface is what is now referred to as cottonwood terrace. The time between 1936 and 1963 (**a** and **b**) represents a stable period where, although tamarisk is present in the canyon, very little additional area of the channel is colonized. Flood magnitudes decreased again in 1962 after the closure of Flaming Gorge Dam and allowed the colonization of a new surface lower than the cottonwood terrace. Photo **c** shows substantial increases in vegetation on the upper island and in the secondary channel around the lower island.

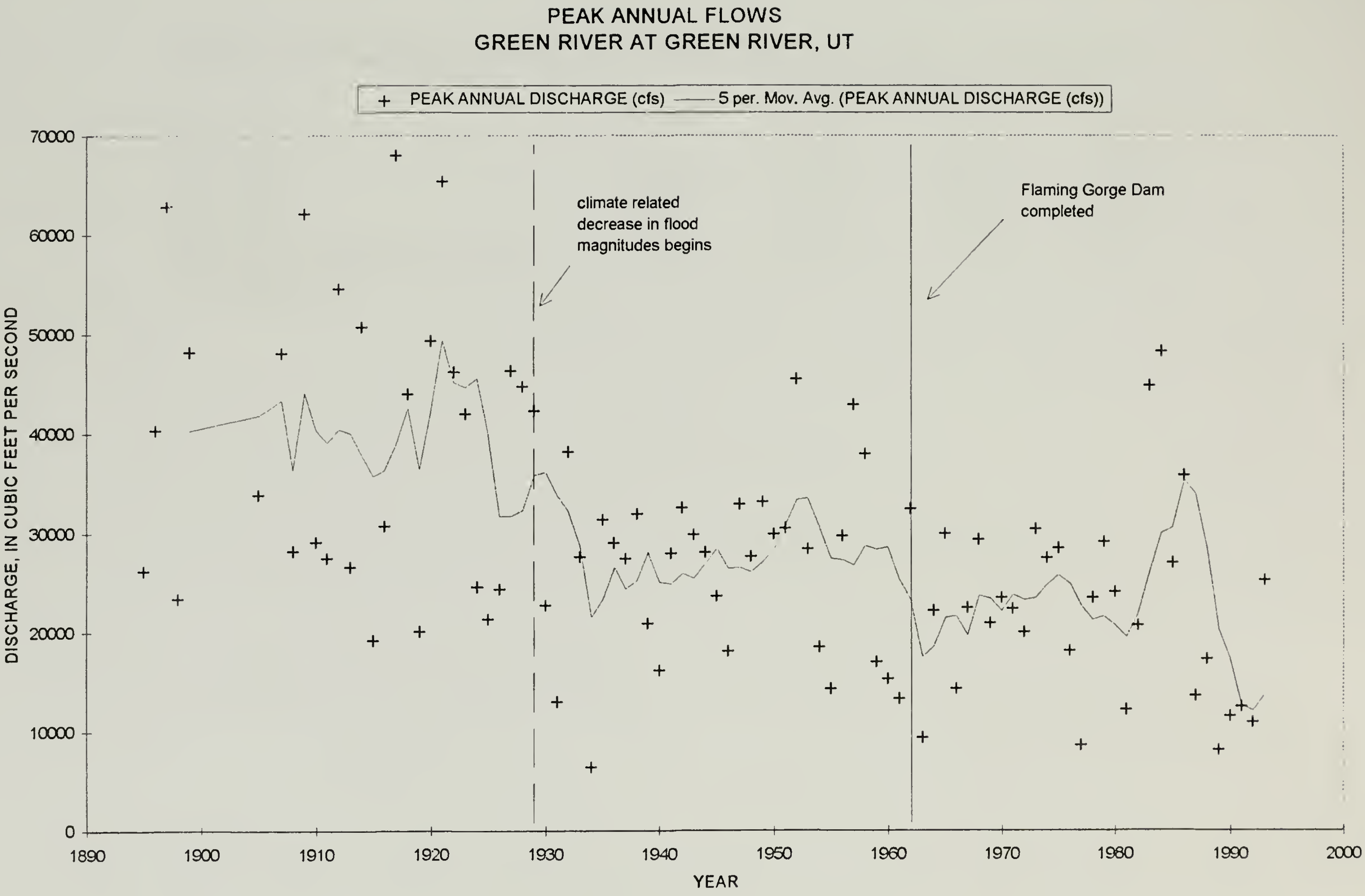


Figure 17. History of peak annual instantaneous discharges for the Green River at Green River, Utah (station 0931500). Plot shows peak flows (plus signs) and a five-year moving average (line). A natural climatic reduction in average flood magnitude occurred in the late 1920's and a dam-induced reduction occurred in 1962.
After Allred (1997)

TABLE 6. DISCHARGES OF SPECIFIC RETURN PERIOD FOR THREE TIME INTERVALS

Time Period	Recurrence Interval			
	1.5 yr. (ft^3/s)	2 yr. (ft^3/s)	5 yr. (ft^3/s)	10 yr. (ft^3/s)
1895-1929*	28250	42025	50850	63840
1930-1957	26130	28250	32666	38490
1963-1993	17940	22425	29310	34610

*No data for 1900-1904, and 1906

from Allred(1997)

Estimation of Degree of Channel Narrowing

Areas mapped as cottonwood terrace were located on the 1936, 1963 and 1993 air photos in order to evaluate whether the mapped terrace was an active surface during earlier times. In a few cases, the 1936 photos show bare sand over the entire area where cottonwood terraces now exist, but in the majority of the cases the air photos showed some vegetation in 1936. The density and areal extent of vegetation had increased by 1963 and covered the majority of areas mapped as cottonwood terrace. Vegetation also increased from 1963 to 1993, and covered the entire area mapped as modern floodplain or vegetated channel-margin fine-grained deposits. In all cases, where areas mapped today as cottonwood terrace were clearly distinguishable on the 1936 and 1963 photos, some portion of that area was unvegetated or part of the active channel in 1936. Because of the increase in vegetation between the oblique 1922 USGS photos, and the 1936 air photos, we estimate that some narrowing had already occurred by 1936.

We assumed, as evidence suggests, that the full extent of the mapped cottonwood terrace was active historically. To estimate narrowing, we calculated the area of the early 1900's channel as the sum of the area of the modern active channel, modern floodplain and the cottonwood terrace (Table 7). The area of the cottonwood terrace plus the modern floodplain, represents the degree of narrowing from the early 1900's channel. The estimate of channel narrowing is the percentage of the original channel that these two surfaces now occupy (Table 8). Using this method, we estimate that the channel has narrowed on average 19 percent in the 4 study reaches since the early 1900s. This estimate is consistent with findings of channel narrowing in other reaches of the Green River (Table 9).

Modern Distribution of Habitats

Although the area of eddies differs between reaches at different discharges, the total area of all eddies in all reaches, when combined, does not significantly change between

TABLE 7. AREA OF MODERN ACTIVE CHANNEL, MODERN AND ABANDONED FLOODPLAINS

	CEDAR RIDGE	SURPRISE	JOE HUTCH	COAL CREEK
AREA OF MODERN ACTIVE CHANNEL (m^2)	875501	966385	1076896	769882
AREA OF MODERN FLOODPLAIN (m^2)	45781	48094	133892	65959
AREA OF COTTONWOOD TERRACE (m^2)	154466	171690	217952	121395

TABLE 8. PERCENTAGE OF HISTORIC ACTIVE CHANNEL NOW OCCUPIED BY VEGETATED INACTIVE SURFACES

	CEDAR RIDGE	SURPRISE	JOE HUTCH	COAL CREEK
COTTONWOOD TERRACE	14.4	14.5	15.3	12.7
MODERN FLOODPLAIN	2.7	3.1	8.7	6.1
TOTAL	17.1	17.6	24.0	18.8

TABLE 9. ESTIMATIONS OF NARROWING OF THE GREEN RIVER'S CHANNEL

AUTHOR	REACH	ESTIMATED NARROWING (PERCENT)	TIME DURATION
ANDREWS	BROWNS PARK	13	1951-1980
GRAMS	LODORE CANYON	22	1950-1993
	ECHO PARK	10	1950-1993
	WHIRLPOOL CANYON	11	1950-1993
	ISLAND PARK	25	1950-1993
	SPLIT MOUNTAIN CANYON	12	1950-1993
ANDREWS	OURAY	13	1964-1978
ORCHARD	DESOLATION CANYON	20	1922-1993
	GRAY CANYON	19	1922-1993
ALLRED	GREEN RIVER NEAR GREEN RIVER, UT	15	1938-1993
GRAF	LABYRINTH AND STILLWATER CANYONS	27	1871-1976

2,100 and 27,000 ft^3/s. The total area of the channel that is within recirculating eddies was measured for 5 discharges in the Cedar Ridge reach and 6 discharges in the other 3 reaches. Total area of eddies was divided by the bankfull channel length to permit comparisons among reaches. A two-factor analysis of variance (ANOVA) without replication was used to determine whether area of eddy was significantly affected by reach, discharge, or both. Results of the ANOVA (Table 10) show that at a 95% confidence interval, the area of eddies, combined for the 4 study reaches, does not change significantly with changes in discharge. The area of eddy at a given discharge did, however, vary significantly by reach. At low discharge, the 4 reaches differ the most in the area of eddies. The Joe Hutch reach has the least area of eddies and the Coal Creek and Cedar Ridge reaches have the highest. At approximately bankfull discharge, all reaches have approximately equal area of eddies.

The area of eddies in each study reach does not systematically increase or decrease with changes in discharge (Fig 18). For example, the area of eddies in the Surprise Canyon reach increases between 2,100 and 16,000 ft^3/s, but then decreases between 16,000 and 27,000 ft^3/s. In contrast, eddy area is smallest in the Coal Creek reach at 12,000 ft^3/s, and is larger at low and bankfull discharge. This variation within reaches is partly explained by the degree the channel is confined by bedrock. In the Joe Hutch reach, the alluvial valley is broad and the channel is seldom in contact with bedrock. Because it is not laterally confined, small changes in discharge can result in large changes in the area of the channel, which in turn creates large changes in the area of eddy. In the Coal Creek reach, the channel is highly confined by bedrock, and changes in discharge do not result in great changes in channel area. Because shorelines have little room to shift in the Coal Creek reach, and because debris fans are steep, obstructions that create eddies persist over a wide range of discharges and the area of eddy varies little.

TABLE 10. TWO-FACTOR ANNALYSIS OF VARIANCE WITHOUT REPLICATION COMPARING AREA OF LOW-VELOCITY HABITAT, BY REACH AND DISCHARGE

DISCHARGE ft^3/s	AREA OF EDDY PER UNIT LENGTH OF CHANNEL			
	CEDAR RIDGE	SURPRISE	JOE HUTCH	COAL CREEK
27000		6.04	8.97	10.38
16200	9.32	10.66	8.88	9.65
12000	5.71	7.65	6.03	8.37
7000	5.97	7.46	6.47	10.22
2500	8.07	6.85	5.41	10.88
2100	8.09	6.41	3.80	9.18

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
27000	3	25.4	8.5	4.9
16200	4	38.5	9.6	0.6
12000	4	27.8	6.9	1.6
7000	4	30.1	7.5	3.6
2500	4	31.2	7.8	5.4
2100	4	27.5	6.9	5.5
CEDAR RIDGE	5	37.2	7.4	2.4
SURPRISE	6	45.1	7.5	2.7
JOE HUTCH	6	39.6	6.6	4.1
COAL CREEK	6	58.7	9.8	0.8

ANOVA

Source of Variation	*df*	*MS*	*F*	*P-value*	*F crit*
Discharge (rows)	5.0	5.3	1.2	0.4	2.9
Reach (columns)	3.0	15.4	3.4	0.0	3.3
Error	15.0	4.5			
Total	23				

TABLE 11. SINGLE FACTOR ANALYSIS OF VARIANCE, COMPARING MEAN EDDY SIZES AT DIFFERENT DISCHARGES

SUMMARY

DISCHARGE	*Number of eddies*	*total area in m ^{2}*	*Average eddy size m ^{2}*	*Variance*
27000	127	228125	1796	5319980
16200	198	336017	1697	5125085
12000	217	242473	1117	2954604
7000	327	262354	802	1829659
2500	234	268385	1147	1950209
2100	230	235043	1022	1417142

ANOVA

Source of Variation	*df*	*MS*	*F*	*P-value*	*F crit*
Between Discharges	5	30933246	11.1	1.6564E-10	2.2
Within Eddies	1327	2783381			
Total	1332				

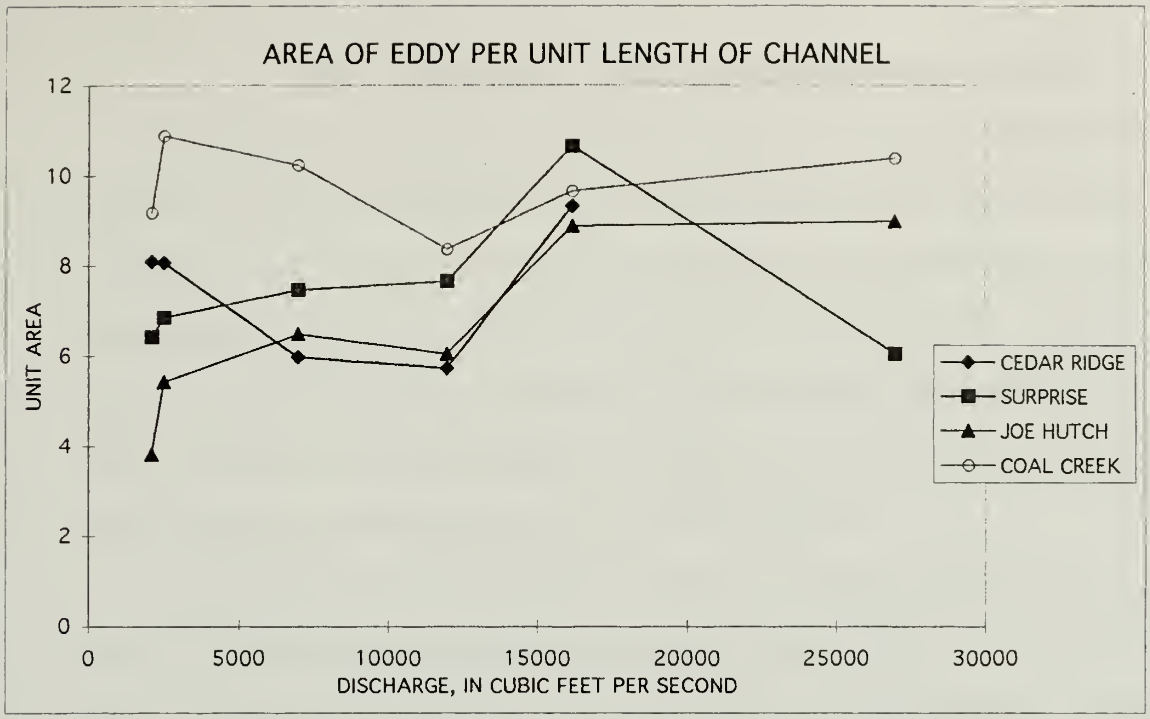


FIGURE 18. The area of eddy in the 4 study reaches did not systematically change with increasing discharge. Area may increase in one reach while decreasing in another, resulting in essentially no net change.

Effect of discharge on size and distribution of eddies

The number and size of individual eddies changes as discharge changes. Typically, large eddies, formed by constrictions in the channel, are present at a very wide range of discharges and get proportionally larger as discharge increases. Smaller eddies, created by irregularities in the shoreline, are very susceptible to changes in discharge. Shoreline eddies may form, change size, or disappear with relatively small changes in flow. The size of eddy is affected by discharge as shown by a single factor ANOVA comparing the mean size of eddies for each discharge value within a reach (Table 11).

The size of eddies within a reach can range over 2 orders of magnitude. At baseflow discharges, the majority of the total area of eddies is created by small shoreline eddies. At higher discharges, shoreline eddies produce only a small fraction of total eddy area, while relatively infrequent large eddies are responsible for the majority of the total area of eddy in a reach. Figure 19 shows a series of histograms of the frequency of eddies within a given size range for all eddies in the 4 study reaches. Each plot represents the frequency of eddies at 1 of the 6 measured discharges. On the second y-axis is a bar graph depicting the percent of the total area of eddy created by eddies within that size class. These plots show that small shoreline eddies increase in frequency from 2,100 to 7,000 ft^3/s and decrease in frequency from 7,000 to 27,000 ft^3/s. Eddies in the largest classes are comparatively infrequent at all discharges but increase slightly at high discharges. At baseflow discharges the small frequent shoreline eddies produce the majority of the area of eddy. As discharge increases, large infrequent eddies, typically formed by constrictions in the channel, are responsible for a higher percentage of the total area.

Distribution of Shoreline Habitats

In the 4 study reaches, shorelines are longest and most complex at baseflow discharges. The complexity of shorelines along a channel is a geomorphic variable which

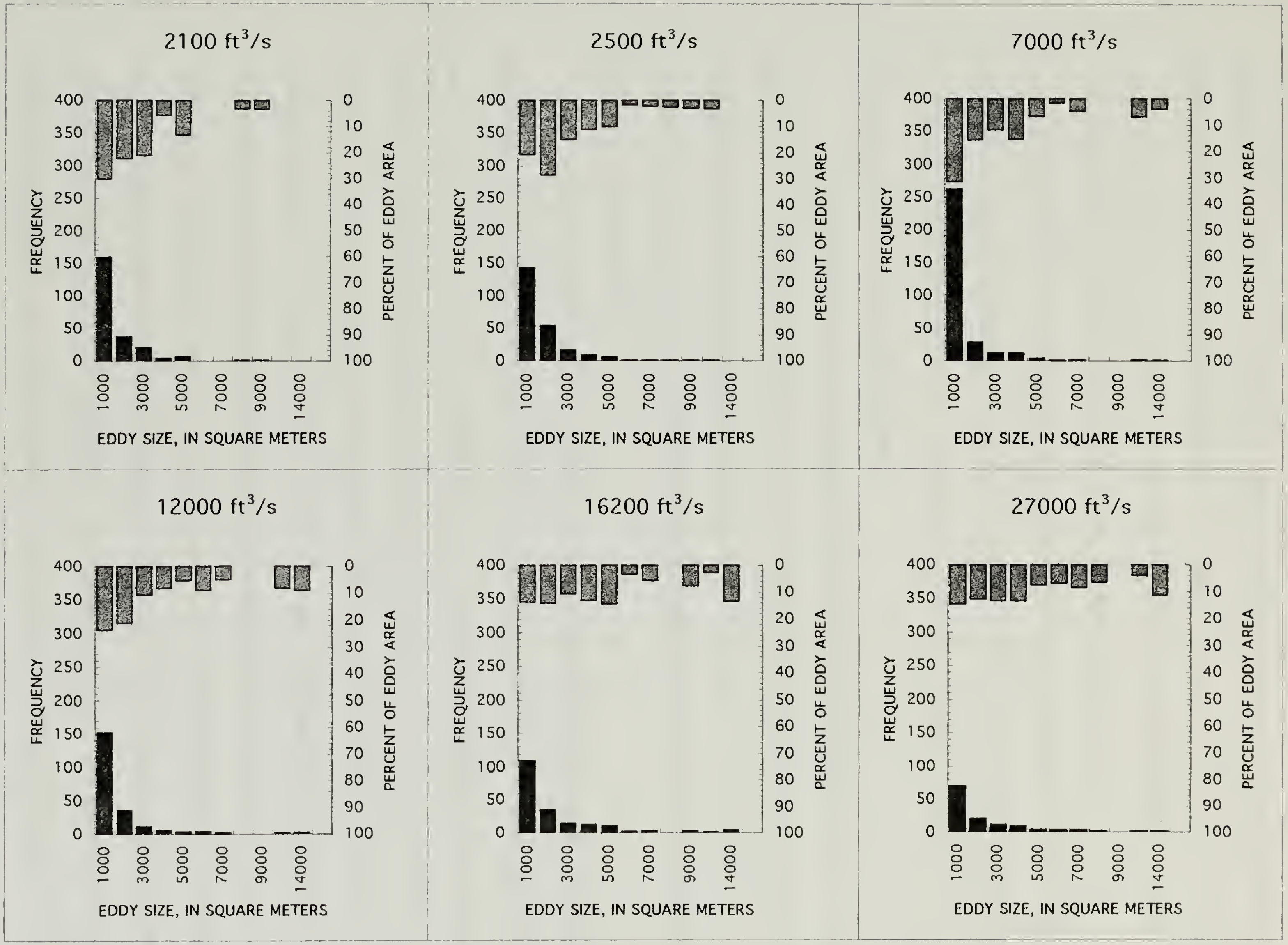


FIGURE 19. Histograms of the frequency of eddies within a given size class. The bar graphs on the secondary y-axis show the percent of the total area of eddy created by eddies in that size class. The plots show that small eddies are most frequent at discharges slightly higher than baseflow. As discharge increases, there are more eddies in the largest size classes, and a greater fraction of the total area is created by these large eddies.

describes the degree that shorelines deviate from a straight line and is calculated by dividing the total length of both shorelines by the mid-line of the channel. A perfectly symmetrical channel such as a flume would have the lowest possible value of 2. Values greater than 2 indicate increasingly convoluted shorelines. Using this index, shorelines in the 4 study reaches are most complex at lower discharges (Fig. 20). In the Cedar Ridge, Surprise Canyon, and Coal Creek reaches, shorelines were most complex at the two lowest measured discharges. In the Joe Hutch reach complexity was greatest at slightly higher discharges. In this reach there are several secondary channels that are dry at baseflow, but become inundated at discharges on the order of 7000 ft^3/s, creating a substantial increase in the total length of inundated shorelines.

The relative abundance of different substrates found in shoreline habitats varied by reach (Fig. 21). The Cedar Ridge reach was the most homogeneous with 10 times as much fine-grained alluvium as the next most abundant shoreline type. The Surprise canyon reach was most heterogeneous in shoreline composition and contains nearly equal representations from each substrate class.

The relative distribution of substrate found in shoreline habitats also changes with discharge. Similar trends in the distribution of specific substrates with changing discharge were observed in each of the 4 reaches (Fig 22). In all cases, vegetation inundated at the shoreline increased with discharge, and unvegetated fines and gravel decreased at the shoreline. Little or no change was observed in the frequency of debris fan, talus, or bedrock shorelines. We used a series of ANOVAs and compared the mean lengths of shorelines from each discharge value in order to determine if the observed changes in the study reaches constitute a significant change that may be extrapolated to the entire canyon reach. Figure 23 shows the mean length of each shoreline type plotted against discharge, and the results of the series of ANOVAs. The findings are that the frequency of vegetated fines, total vegetation and bare sand occurring in shoreline habitats, were significantly affected by discharge at the 95-percent confidence level. The effect of discharge on the

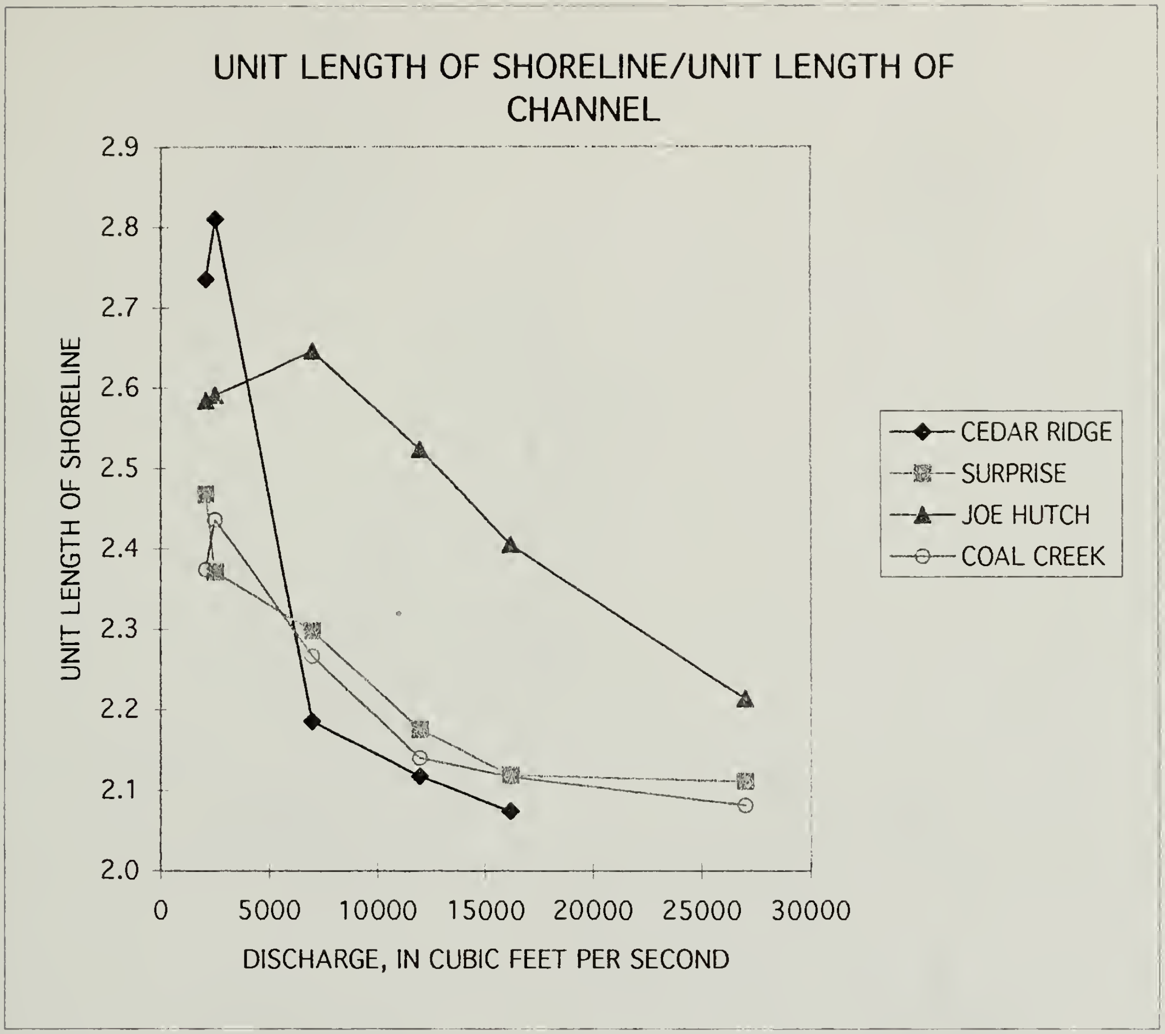


Figure 20. Shoreline complexity values for shorelines in the 4 study reaches at a wide range of discharges. Values are computed as the length of shoreline divided by the length of the centerline of the channel. Higher numbers indicate more complex shorelines.

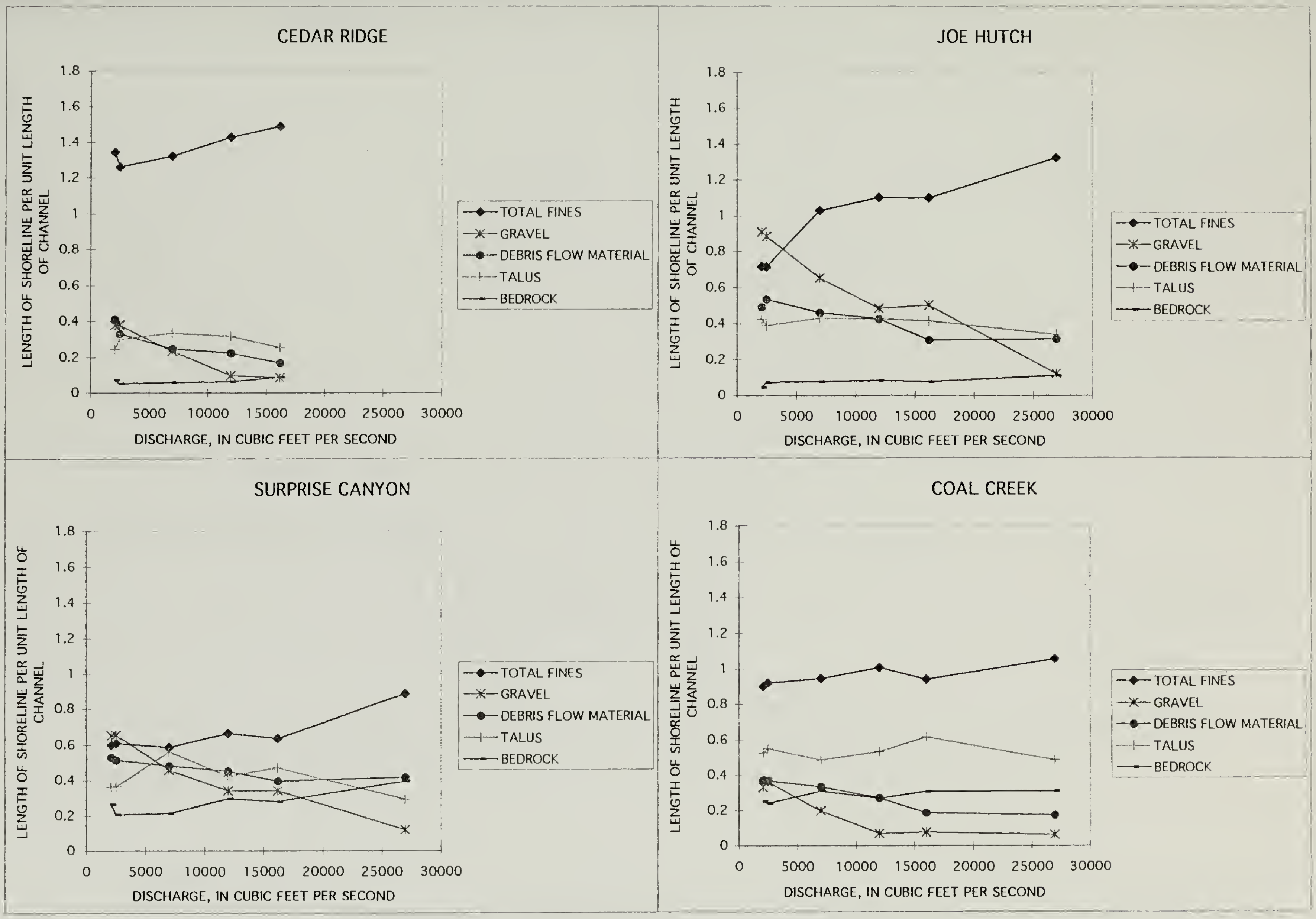


Figure 21. Plots showing the distibution of bank-material inundated at the shoreline in the 4 study reaches, at a wide range of discharges. The plots show how the composition of bank-material varies by reach and discharge. Shorelines in the Cedar Ridge reach are predominantly fine-grained alluvium. In the Surprise Canyon reach there is more coarse material inundated along shorelines. In all reaches the abundnce of gravel shorelines decreaces with increasing discharge.

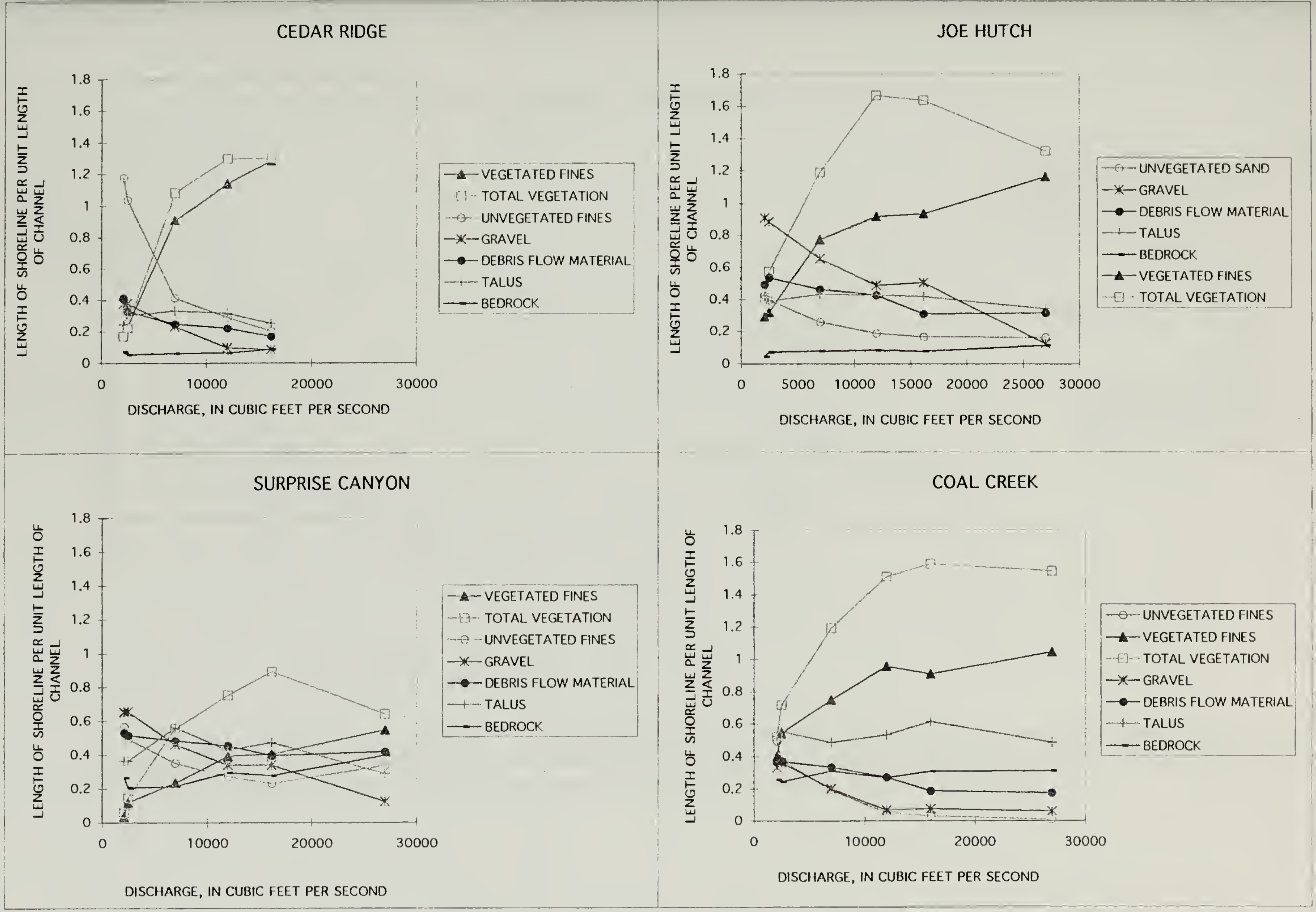
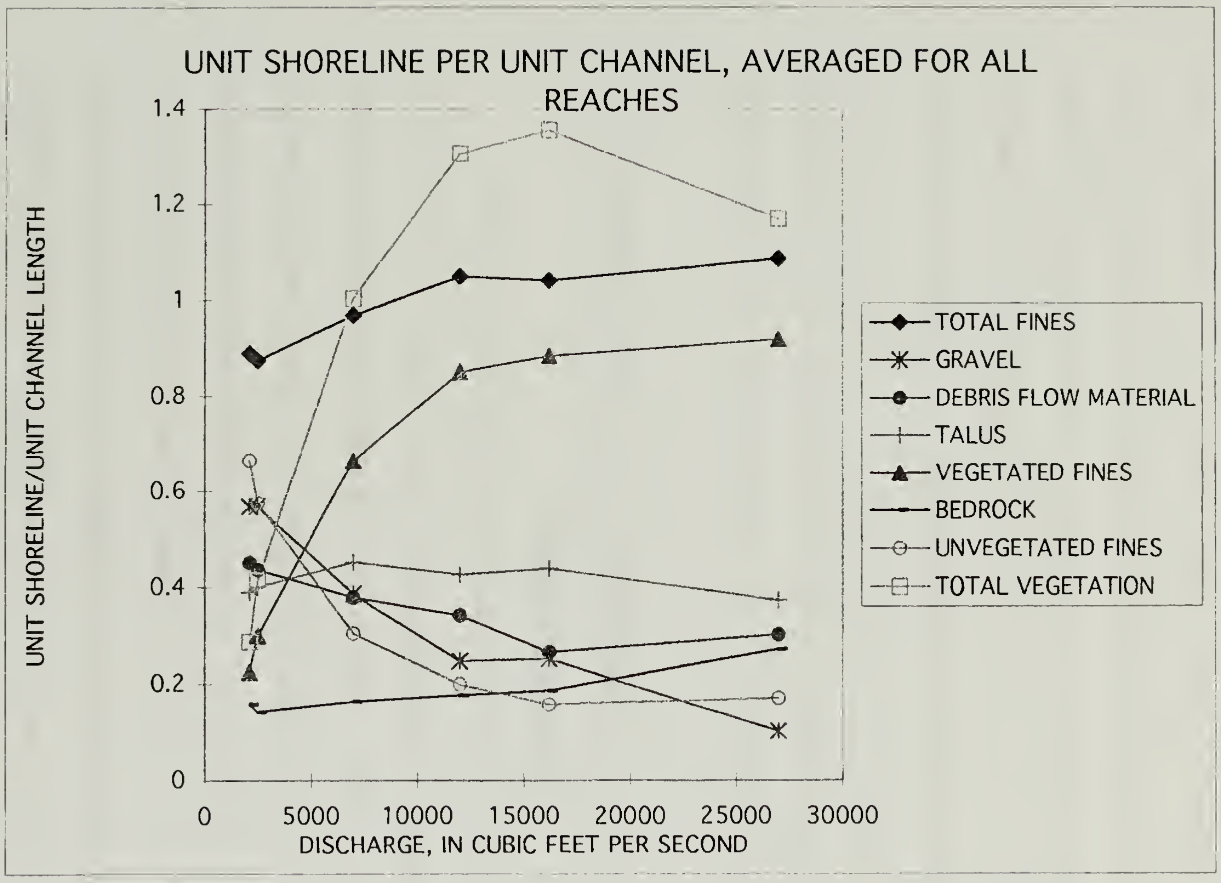


Figure 22. Plots showing the distribution of bank-material and vegetation inundated at the shoreline in the 4 study reaches, at a wide range of discharges. At low discharges, shorelines are predominantly bare fine-grained alluvium and gravel. As discharge increases, the amount of vegetated shorelines increase and the amount of bare fine-grained alluvium and gravel decreases. The difference in the vegetated fine-grained alluvium curve and the total vegetation curve represents the amount of vegetation on coarse material. Distributions of talus, debris fan material and bedrock shorelines remain essentially constant with changing discharges.



ANOVA single factor	F CRITICAL
comparing length of specific shorelines with discharge	2.8100
	F
TOTAL FINES	0.3079
GRAVEL	2.7722
DEBRIS FLOW MATERIAL	1.8903
TALUS	0.2697
BEDROCK	0.4771
VEGETATED FINES	4.5212
UNVEGETATED FINES	4.0687
TOTAL VEGETATION	7.4271

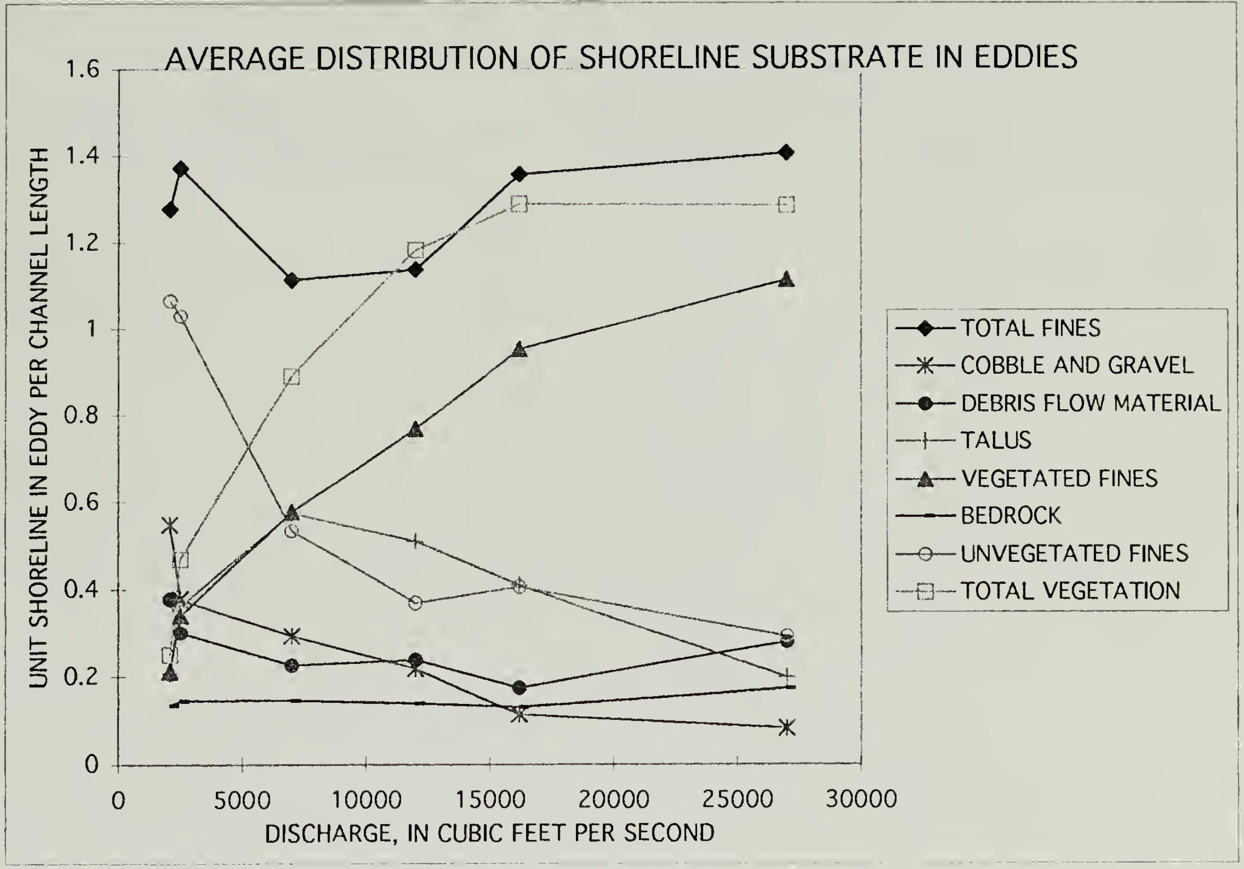
Figure 23. Plot showing the average length of shorelines containing a specific substrate or inundated vegetation. Analysis of variance was used to compare the mean length of each shoreline class with discharge. There is a significant decrease in the amount of bare fine-grained alluvium and gravel found in shoreline habitats as discharge increases, and a significant increase in inundated vegetation.

abundance of cobble-gravel shorelines was more subtle but was significant at the 90-percent confidence level. Discharge did not significantly influence the frequency of debris fan, talus or bedrock shorelines.

Discharge was shown to have a greater effect in determining shoreline substrate within eddies, than it does in the channel as a whole. Composition of shorelines in eddies varies from the rest of the channel. Per unit shoreline there is more fine grained alluvium, both vegetated and bare, in eddies than in the rest of the channel. Talus also represents a larger percentage of the shoreline in eddies than in the channel as a whole. Figure 24 shows the distribution of shoreline habitats occurring in eddies, for each reach. In eddies, unlike the main channel, changing discharges caused significant changes in the amount of debris fan and talus shorelines. The amount of gravel, bare sand, vegetated sand, and total vegetation, also changed significantly with discharge. Vegetated fines, and total vegetation inundated along shorelines in eddies increased significantly with discharge, while bare sand, gravel, and debris fan shorelines decreased. The amount of talus shorelines in eddies peaked near 7000 ft^3/s and declined at higher discharges. At any given discharge approximately 25 percent of shorelines occur within eddies (Table 12).

Conceptual Model of the Distribution of Shoreline Habitats Prior to Channel Narrowing

Narrowing of the channel, and the substantial increases in vegetation on low-elevation surfaces along the channel, constitute significant changes in the geomorphology of the Green River in Desolation and Gray Canyons. These changes have likely altered the relationship between habitat and discharge that existed early in the century when the humpback chub was not a threatened species. The most dramatic changes in habitat have occurred along shorelines where vegetation has invaded. Historic photos show that the channel was scoured free from vegetation across a much wider area than at present. It appears from the photos that vegetation did not become inundated in the historic channel



ANOVA single factor 95% CONFIDENCE INTERVAL	F CRITICAL 2.810
comparing length of specific shorelines in eddies with discharge.	F
TOTAL FINES	1.83
GRAVEL	4.70
DEBRIS FLOW MATERIAL	2.87
TALUS	2.79
BEDROCK	0.10
VEGETATED FINES	9.01
UNVEGETATED FINES	6.32
TOTAL VEGETATION	7.31

Figure 24. Composition of shorelines in eddies varies from the rest of the channel. Shorelines in eddies contain more fine-grained alluvium and talus than other shorelines. The type of substrate inundated along shorelines in eddies is controlled by discharge, more so than in the main channel. Increasing discharge causes significant decreases in gravel, debris flow material, and unvegetated fine-grained alluvium, as well as significant increases in inundated vegetation. Discharge also influenced the abundance of inundated talus shorelines, which peak around 7,000 ft^3/s.

TABLE 12. PERCENTAGE OF THE TOTAL SHORELINE WITHIN EDDIES

DISCHARGE ft^3/s	CEDAR RIDGE	SURPRISE	JOE HUTCH	COAL CREEK
27000		21	27	24
16200	27	31	24	29
12000	24	26	21	22
7000	24	25	26	36
2500	26	23	22	36
2100	26	25	15	31

until near bankfull conditions. To simulate these conditions we recomputed habitat/discharge relationships developed for existing conditions, but eliminated vegetation map units (Fig. 25).

Before the onset of channel narrowing, bare sand would have been the dominant bank-material in shoreline habitats at all discharges up to 27,000 ft^3/s, which is the highest discharge we have data for. Changes in discharge would have had a lesser effect on the type of substrate inundated in habitats than they do at present. Increasing discharges would have only decreased the amount of inundated gravel in shorelines, whereas today, increasing discharge causes decreases in bare sand and increases in vegetation. Because the historic channel was largely free of vegetation, the conditions we observe today at baseflow --highly convoluted shorelines, abundant shoreline eddies, and unvegetated low level sand and cobble bars-- would have persisted in the historic channel over a much wider range of discharges than they do at present. This suggests that, prior to channel narrowing, habitat conditions along shorelines were less sensitive to changes in discharge than at present. Habitat conditions today are probably much more variable with changes in discharge, and as a result, habitat conditions that benefit humpback chub may be restricted to a narrower range of discharges than in the past.

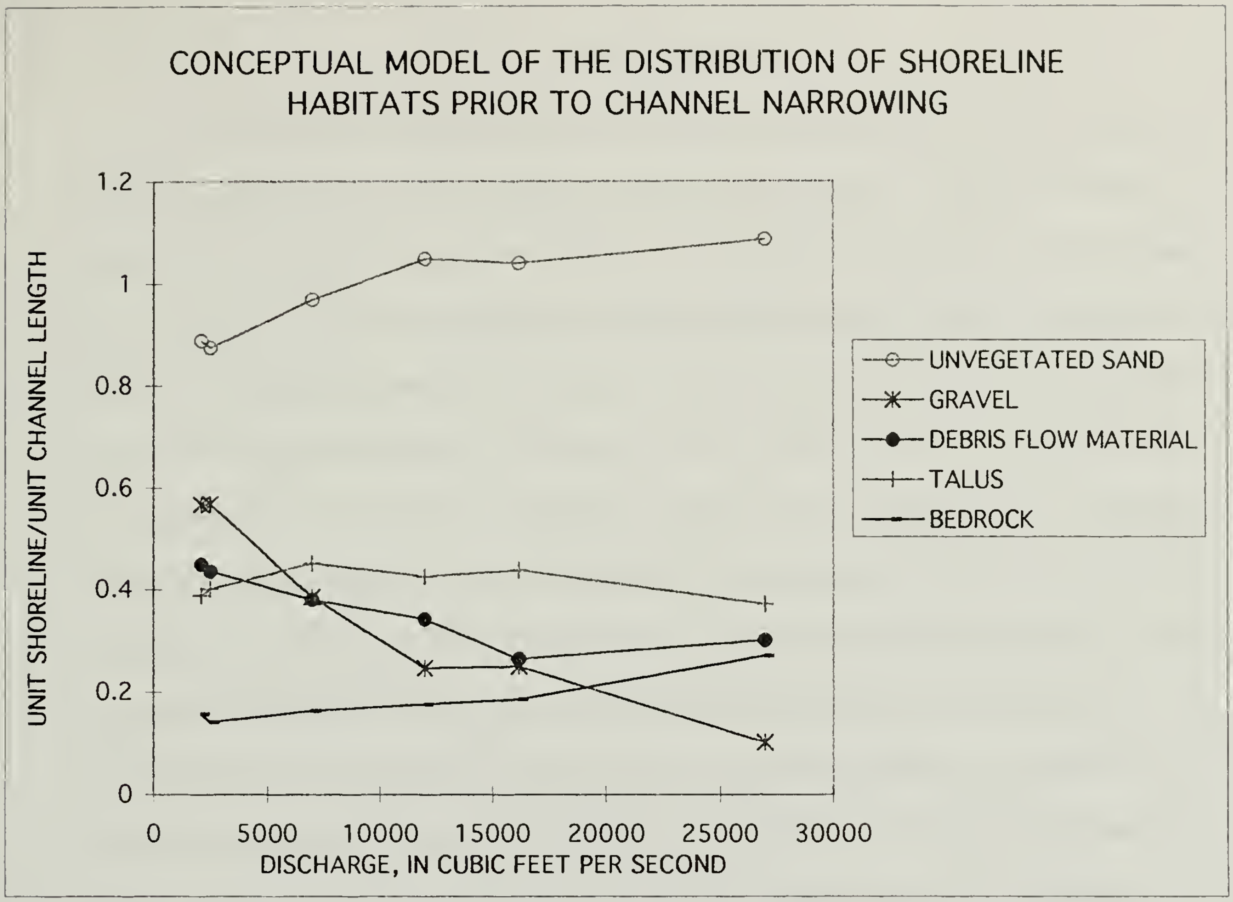


Figure 25. Plot showing what the distribution of shoreline habitats may have been prior to channel narrowing. Only the abundance of gravel shorelines changed significantly with increasing discharges. Unvegetated sand was the dominant substrate in shoreline habitats at all discharges up to 27,000 ft^3/s.

DISCUSSION

The results of this study demonstrate that habitat availability in the Green River in Desolation and Gray Canyons is strongly influenced by discharge. Although the total amount of low-velocity habitat does not change, the condition and location of the habitat changes greatly. The size and number of eddies changes with discharge such that the total area of low-velocity habitat does not change. Eddies increase in frequency and decrease in size as discharge increases from baseflow to about 7,000 ft^3/s. Above 7,000 ft^3/s eddies become larger but less frequent, resulting in essentially no net change. At low discharges, the majority of the area of low-velocity habitat occurrs as small shoreline eddies. At high discharges, the majority of the low-velocity habitat occurs as large as large eddies formed by channel constrictions. The total length of inundated shorelines, the complexity of shoreline habitats, and the relative abundance of inundated vegetation, bare sand, and cobble bars along shorelines are all determined by discharge. Low discharges result in highly complex shoreline habitats with dominantly bare sand and gravel substrates. Increasing discharge submerges bare sand and cobble bars, and substantially increases the amount of inundated vegetation along shorelines.

In Desolation and Gray Canyons, the area occupied by the active channel has decreased on average 19 percent since the beginning of this century. Two episodes of narrowing have occurred, evidenced by two new and distinct surfaces that have formed this century. The cottonwood terrace is an abandoned floodplain that began to stabilize between 1922 and 1936 as a result of naturally-occurring climate change. After the closure of Flaming Gorge Dam a second lower surface, the modern floodplain, has become densely colonized by riparian vegetation and is accumulating sediment by the process of vertical accretion. In reaches upstream and downstream from Desolation and Gray Canyons, vertical accretion and channel simplification have caused the loss of secondary channels and the elimination of substantial habitat (Allred 1997, Graf 1978) . Vertical accretion has

caused the closure of one secondary channel in the reaches we observed in this study. The secondary channels around several other islands have been colonized with substantial vegetation, which is an indication that the channels are stabilizing and being abandoned. In this study we have found no evidence that the episode of channel narrowing observed between 1963 and 1993 has abated. It is likely that vegetation will continue to increase in density on low-elevation surfaces resulting in additional channel narrowing and the accompanying loss of habitat.

ACKNOWLEDGMENTS

Susan P. Holman's and Jared Farmer's photographic contributions were an essential part of this study, and great thanks goes to them for their hard work and expertise. Additional thanks to Dennis Willis and the Bureau of Land Management's Price Ranger District, for their willingness to provide logistical support and access to these canyons. Numerous dedicated technicians also made significant contributions to this project, and special thanks and appreciation goes to them. Megan Barker, Michelle Brink, Anne Howard, and Dale Munson deserve special thanks for their efforts as technicians, and for the support they have given as friends. Most importantly, special thanks and appreciation goes to my wife and daughter, Amy and Sonora Orchard, for sharing with me the beauty of Desolation Canyon.

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APPENDIX A
SUMMARY OF PHOTOGRAPHIC INFORMATION

Photographer	Date of Original	Photo Id	Source	Subject of photo	Date matched	Photographer	Rkm	Increase in riparian vegetation	Evidence of channel narrowing
E. O. Beaman	15-Aug-1871	714	National Archives	debris fan	9-Jun-1995	J. Farmer	287	Yes	No
R. Wooley	7-Jun-1917	19916	University of Utah Special Collections	Surprise rapid	17-Jun-1995	J. Farmer	282	Yes	Yes
M. Merriman	Nov-1940	Tabyago Dam site	Bureau of Reclamation, SLC UT	alluvial valley	13-Jun-1995	J. Farmer	333	Yes	Yes
M. Merriman	Nov-1940	Gold Hole Dam site	Bureau of Reclamation, SLC UT	channel	13-Jun-1995	J. Farmer	324	Yes	No
R. Wooley	9-Jan-1922	32188	University of Utah Special Collections	alluvial valley	13-Jun-1995	J. Farmer	312	Yes	Yes
M. Merriman	Nov-1940	Flat Canyon Dam site	Bureau of Reclamation, SLC UT	channel margin	15-Jun-1996	S.P. Holman	294	Yes	Yes
R. Wooley	6-Sep-1922	32207*	University of Utah Special Collections	mid-channel bar	15-Jun-1996	S.P. Holman	292	Yes	Yes
R. Wooley	7-Sep-1922	32220	University of Utah Special Collections	Surprise rapid	5-Sep-1996	S.P. Holman	282	Yes	Yes
R. Wooley	7-Sep-1922	32221	University of Utah Special Collections	channel	16-Jun-1996	S.P. Holman	281	Yes	Yes
R. Wooley	7-Sep-1922	32225	University of Utah Special Collections	channel	6-Sep-1996	S.P. Holman	280	Yes	Yes
M. Merriman	Nov-1940	Snap Canyon Dam site	Bureau of Reclamation, SLC UT	alluvial valley	17-Jun-1995	J. Farmer	277	Yes	No
R. Wooley	9-Sep-1922	32237*	University of Utah Special Collections	alluvial valley	7-Sep-1996	S.P. Holman	273	Yes	Yes
M. Merriman	Nov-1940	Three Canyon Dam site	Bureau of Reclamation, SLC UT	alluvial valley	18-Jun-1995	J. Farmer	272	Yes	Yes
R. Wooley	9-Sep-1922	32241	University of Utah Special Collections	alluvial valley	7-Sep-1996	S.P. Holman	271	Yes	Yes
R. Wooley	10-Sep-1922	32245*	University of Utah Special Collections	mid-channel bars	8-Sep-1996	S.P. Holman	259	Yes	Yes
R. Wooley	10-Sep-1922	32254*	University of Utah Special Collections	point bar	8-Sep-1996	S.P. Holman	257	Yes	Yes
R. Wooley	10-Sep-1922	32255	University of Utah Special Collections	alluvial valley	8-Sep-1996	S.P. Holman	254	Yes	Yes
R. Wooley	4-Jun-1917	19885	University of Utah Special Collections	mid-channel island	19-Jun-1996	S.P. Holman	249	Yes	Yes
R. Wooley	11-Sep-1922	32262	University of Utah Special Collections	Rabbit Valley Rapid	8-Sep-1996	S.P. Holman	238	Yes	Yes
R. Wooley	12-Sep-1922	32277	University of Utah Special Collections	mouth of Price River	9-Sep-1996	S.P. Holman	224	Yes	Yes

* Photos in report

APPENDIX B

DESCRIPTION OF MAP UNITS

ALLUVIAL DEPOSITS OF THE GREEN RIVER IN DESOLATION AND GRAY CANYONS

ALLUVIUM OCCURRING IN THE ACTIVE CHANNEL

Bars formed as channel margin deposits

channel margin silts and muds	Terrace like deposit with abundant silts and muds. Deposit is highly cohesive, and is slippery and sticky when wet. Bedding is horizontal and bedforms such as ripples are absent. Deposits are most common where flow velocities are very low such as in reaches above a major constriction in the channel.
channel margin sand	Sand occurring along the margin of the channel in zones of downstream flow. May be horizontally bedded or contain small bedforms such as ripples. These deposits typically occur at very low elevations in the channel and are only exposed at very low discharges.
submerged sand	Fine grained alluvium submerged but visible at the time of mapping
mid channel sand bar	Sand bar occurring in downstream flow and unattached from the bank
gravel	Coarse, sub to well-rounded material which has been transported by the river. Material is moderately to well-sorted, often imbricated. Most often occurs downstream from active debris fans and at low elevations in the active channel. Typically occurs at very low elevations in the channel and is only exposed at low discharges.
Submerged gravel	cobble and gravel sized deposits submerged but visible during mapping.
vegetated gravel	vegetated gravel bar. Vegetation is typically willow or young tamarisk and is sparse compared with vegetated fine-grained alluvial deposits. Deposit is typically higher in elevation than bare gravel and often is overlain by a thin veneer of sand or mud

Bars formed in recirculating flow

separation bar	Sand deposited in recirculating flow. Separation bars occur as a veneer of sand on the lee side of debris fans where downstream current separates from the bank.
vegetated separation bar	Vegetated upper portion of a separation bar. Vegetation is typically young willow. Although they are vegetated, these deposits are typically lower in elevation and more sparsely vegetated than the floodplain. They are more frequently inundated than the floodplain and vegetation is subject to frequent scouring.
reattachment bar	Sand deposited in recirculating flow. Reattachment bars are paired with, and occur downstream of separation bars. They form at the downstream end of recirculating eddies where downstream flow reattaches with the bank.
vegetated reattachment bar	Vegetated upper portion of a reattachment bar. Vegetation is typically young willow. Although they are vegetated, these deposits are typically lower in elevation and more sparsely vegetated than the floodplain. They are more frequently inundated than the floodplain and vegetation is subject to frequent scouring.
eddy bar	Undifferentiated sand bar deposited in recirculating flow.
vegetated eddy bar	Vegetated upper portion of an eddy bar. Vegetation is typically young willow. Although they are vegetated, these deposits are typically lower in elevation and more sparsely vegetated than the floodplain. They are more frequently inundated than the floodplain and vegetation is subject to frequent scouring.

COLLUVIUM DEPOSITED IN THE ACTIVE CHANNEL

active channel debris fans	Debris fan material regularly inundated by the active channel. These deposits occur on the extreme distal end of debris fans where the fan is in contact with the channel. Fines and small clasts are winnowed away during inundation, leaving generally large angular rocks and boulders behind. These deposits cause

	constrictions in the main channel and often form riffles and rapids.
active channel vegetated debris fans	Distal portion of debris fans which are in contact with the channel and inundated frequently. Riparian vegetation sometimes occurs along the channel margin on debris fan material, but is rare compared to vegetation on fine-grained alluvium. Vegetation is typically willow.
active channel talus	Unconsolidated alluvium deposited by rockfall, or as scree at the bottoms of hillslopes, into the active channel. Generally highly angular with large interstitial spaces.
channel margin sand on talus	Intermittent small sandbars which occur between large blocks of talus. These sands are deposited by small eddies created by irregularities in the talus shoreline.
vegetated fines on talus	Fine-grained alluvium deposited by small eddies which occur along talus shorelines. Vegetation, typically willow or tamarisk, has established on the small pockets of sand that fill the interstitial spaces between talus blocks.

SURFICIAL DEPOSITS IN THE ALLUVIAL VALLEY, WHICH ARE NOT PART OF THE ACTIVE CHANNEL

alluvial deposits

vegetated channel margin fines	This deposit is the modern floodplain. It is a densely vegetated terrace-like fine-grained alluvial deposit, occurring adjacent to the active channel. It is typically higher in elevation than sands deposited in the active channel. This surface is inundated less frequently than deposits in the active channel, but is overtopped by flooding roughly 2 out of every 3 years.
cottonwood terrace	Terrace consisting of fine grained alluvium bordering the channel margins. Cottonwood terrace is higher in elevation than the modern floodplain, and is no longer inundated. This surface is an abandoned floodplain and is often vegetated by mature tamarisk, box elder, and cottonwood trees. Non-riparian vegetation such as cactus and sage brush can be found on this surface. Driftwood at this elevation is highly weathered, but contains evidence of historic inundation, such as sawn logs in drift piles.
high terrace	Terrace like deposit of fine grained alluvium. High terrace is higher in elevation than cottonwood terrace. High terrace is often vegetated with pinion and

	juniper trees and has abundant cryptogramic crusts on the soil surface. Does not contain evidence of historic inundation. Stratagraphic exposures often show intertounging with debris-fan material.
undifferentiated terrace	cottonwood/high terrace undifferentiated
cultivated terrace	undifferentiated terrace level which has been plowed and cultivated such that the cottonwood and high terrace are not discernible from each other. Small boulders and rocks have been cleared from debris fan surfaces adjacent to this alluvial terrace and plowed as well, so that the contact between the alluvial terrace and debris fan material is vague.

colluvium

inactive debris fan	High elevation debris fan material which is not subject to inundation by the river. Inactive debris fans are vegetated with desert shrubs. Exposed rock often is blackened with desert varnish and shows signs of weathering such as pitting. Material is transported during episodic flash floods of tributary canyons as debris flows. When the debris flows reach the alluvial valley, they spread out, loose energy and are deposited. Material may be deposited directly in the active channel, or may be deposited on the fan surface at elevations higher than the active channel. Debris fan material is unsorted, and size ranges from silts and sands to boulders. Clasts are angular and often matrix supported. These are the most extensive deposits in the alluvial valley in Desolation Canyon.
active debris fans	Debris flow deposits that show signs of historic activity. These are typically the channels which have been incised into older debris fan material during recent flash flooding or debris flow events. There is little or no vegetation and rocks often appear buff in color. Active debris fans contain sorted gravels which are worked during flash flooding, and also contain unsorted matrix supported clasts.

eolian deposits

eolian sand	Wind blown sand deposit. Eolian sand generally occurs adjacent to large recirculating eddies whose sandbars act as source areas. Deposits are often expansive and form tall steep dunes. Dunes are vegetated with grasses and small shrubs

PLATES 1 - 4

SURFICIAL GEOLOGY OF THE ALLUVIAL VALLEY IN 4 REPRESENTATIVE REACHES OF DESOLATION AND GRAY CANYONS